Keep Your Card in This Pocket

CLIMATIC LAWS

NINETY GENERALIZATIONS WITH NUMEROUS COROLLARIES AS TO THE GEOGRAPHIC DISTRIBUTION OF TEMPERATURE, WIND, MOISTURE, ETC.

A SUMMARY OF CLIMATE

BY

STEPHEN SARGENT VISHER, Ph.D.

Fel. Amer. Meterol. Soc., Royal Geog. Soc., Assoc. Amer. Geogrs. etc.
Associate Professor of Geography, Indiana University

NEW YORK
JOHN WILEY & SONS, Inc
London CHAPMAN & HALL, Limited
1924

Printed in U. S. A.

To

Julius Hann, 1838-1921, Austrian

Who was for forty years the leading climatologist of the world

And who formulated many climatic generalizations

and to

William Morris Davis, 1850-, and Frank Waldo, 1857-1920

Americans

Who in the early 1890's formulated such laws as they could from the data then available

PREFACE

Concise statements of the ways in which certain aspects of climate differ from place to place are given in some texts and treatises dealing with meteorology and climatology. Similar brief statements of how nature acts have been helpful in advancing many other sciences. These "laws", as they have been termed, call attention to what is known, and often reveal the inadequacies of current knowledge. An attempt is here made to state, explain and illustrate what in lieu of a better short title, may be called "the laws of climate." Many of these are obviously not strictly analogous to some of the laws of the more exact sciences, but the term "law of nature" is not applied merely to precise quantitatively demonstrable laws. The aim of this treatise is to point out and explain those relations which correspond, in so far as the nature of the subject permits, to the laws of other sciences. Like those laws, these relations are subject to frequent modification, and seldom do they operate in a dominating way. However, neither do many laws of physics, for example, operate except under restricted conditions of temperature, pressure, purity of substance, etc.

Many of the laws here given have been expressed or implied in one or more of the treatises or texts consulted[1] or in technical papers. Hann has formulated more than any other author but Davis and Waldo have each offered several climate generalizations, and many other writers one or two each. A number of the laws of this treatise seem not to have been concisely stated in print, however, and many have not been fully explained. In order to have fewer omissions and more accurate and

[1] *Meteorologies*: Davis (1894), Russell (1895), Waldo (1894) (1896), Moore, J. (1894, 1910), Moore, W. L. (1910), Milham (1912), Hann, Lehrbuch der Meteorologie, 3d ed. (1915); McAdie (1917), National Research Council (1918), Shaw, *Manual of Meteorology*, pt. IV (1919; Lempfert (1920), Humphreys, *Physics of the Air* (1920). *Physiographics*: Salisbury (1907, 1919), Tarr-Martin (1914). *Miscellaneous:* Ward, *Climate* (1908, 1918); Hann; *Handbook of Climatology* (1903); Huntington, *The Climatic Factor* (1914); Henry and others, *Weather Forecasting in the U. S.* (1916); Salisbury, Barrows and Tower, *Elements of Geography* (1912); Shaw and others, *Meteorological Glossary* (1918); Ferrel, *Popular Treatise of Winds* (1889); Shaw, *Weather Forecasting* (1911, 1919); Taylor, *Australian Meteorology* (1920). *Physics*: Ganot (1905), Watson (1899), Crew (1909), Kimball (1917), Poynting-Thompson (1911).

clearer statements of these laws and their causes, criticisms were obtained from a number of persons. Grateful acknowledgment is here made to all who have so generously assisted in making this study more worth while.*

A summary of the incompleted study was published in the Journal of Geography, Vol. XX, pp. 252-264, Oct. 1921, and in The Geographical Teacher (London) Vol. XI, pp. 45-51, summer 1921. The Laws of Temperature, Winds and Moisture were published in The Annals of the Association of American Geographers, Vol. XIII, pp. 15-40, 169-207, March and December 1923.

The author hopes that this little volume will make it somewhat less difficult for students of climate to obtain an understanding of this important subject. If, in addition, this attempt to formulate the laws of climate leads to fuller knowledge of climate and of the geographic environment of man, he will be doubly pleased.

Bloomington, Ind., February 20, 1924.

S. S. V.

*C. F. Brooks, Clark University; E. M. Brown, R. I. College for Teachers; C. C. Colby, University of Chicago; E. R. Cumings, Indiana University; William Morris Davis, Harvard University; P. C. Day, U. S. Weather Bureau; R. E. Dodge, Storrs, Conn.; C. R. Dryer, Fort Wayne, Ind.; J. Paul Goode, University of Chicago; A. J. Henry, U. S. Weather Bureau; T. C. Hopkins, Syracuse University; W. J. Humphreys, U. S. Weather Bureau; E. Huntington, Yale University; M. M. Leighton, University of Illinois; B. E. Livingston, Johns Hopkins University; W. N. Logan and C. A. Malott, Indiana University; A. McAdie, Blue Hill Observatory; W. I. Milham, Williams College; G. J. Miller, Teachers College, Mankato, Minn.; A. E. Parkins, George Peabody College for Teachers; T. T. Quirke, University of Illinois; R. D. Salisbury, University of Chicago; C. O. Sauer, University of Michigan; H. E. Simpson, University of North Dakota; J. Warren Smith, U. S. Weather Bureau; E. Van Cleef, Ohio State University; O. D. von Engeln, Cornell University; R. DeC. Ward, Harvard University; C. M. Zierer, Indiana University.

Drs. Brooks, Huntington and Humphreys have been especially helpful as to content and Drs. Salisbury, Malott and Zierer as to form.

CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTORY: TWENTY-FIVE METEOROLOGICAL LAWS

In order that the climatic factors, or the influences controlling climate, may be understood, a number of meteorological laws must be held clearly in mind. Twenty-five such laws may be stated briefly as follows:

Group 1. Temperature

1. The earth's surface is warmed chiefly by solar radiation, and to a lesser extent by radiation from the warmed atmosphere.

2. The earth's surface is cooled chiefly by outward radiation to the overlying air, which is thereby warmed and then usually rises carrying the heat to higher levels where it readily escapes into space. A secondary method of cooling is that which accompanies evaporation and thawing. A third method, radiation into space, is also important in high altitudes and in dry regions.

3. The lower atmosphere is warmed chiefly by the absorption of terrestrial radiation and to a minor degree by the absorption of solar radiation.

4. The lower air is cooled chiefly by convection, i.e., the rising of the warmed air, and subsequent radiation to cooler air and into space. It is sometimes cooled by radiation to cooler land or water.

5. Vertical rays from the sun are more effective in warming the earth than are oblique rays; the more oblique the rays, the less heat received. Rays which are reflected from the earth have no effect on terrestrial temperature.

6. As all atmospheric molecules and especially water vapor interfere with the passage of heat, the drier and the thinner the air the greater the heating by rays coming from the sun at a given angle, and the more rapid the cooling by night and in the shade.

7. Heat is carried from place to place mostly by winds and to a lesser extent by ocean currents.

8. Water warms less easily and more slowly than land, and cools more slowly because (a) the specific heat of water is about twice that of land; (b) water is warmed to a greater depth, because of transparency and convection, and hence the surface layer is not warmed so much; (c) there is more reflection from water than from land; (d) there is usually more evaporation from water than from land. The slower cooling of the water is because of (a) and (b), and because water vapor

and clouds are more abundant over water than over land. Water vapor and clouds hinder the escape of heat.

9. The temperature of an object increases until the loss of heat equals the addition of heat. When the loss and the gain balance, the temperature remains constant. When the loss exceeds the gain, the temperature falls. Therefore maximum temperatures occur after the time of maximum heating, and minimum temperatures occur after the time of maximum loss of heat by radiation. In other words, there is a daily and seasonal lag.

10. Evaporation is a cooling process; when condensation occurs, as much heat is released as was required to evaporate the condensed vapor. However, since most condensation occurs high up in the air where the heat can easily escape to space, the final result of evaporation is usually surface cooling.

11. Rapid descent warms air while rapid ascent cools it. The adiabatic cooling of dry air while ascending is at the rate of 1°F. for each 200 feet, approximately.

As a summary of these laws of heating it may be well to picture the cycle due to their joint action. The sun rises; its rays penetrate the air but are absorbed by the dark soil which thereby is warmed and gives out long heat rays which are absorbed by the air. As the air becomes warm it expands. Winds are set up, and the heated air is moved away and warms other places, where the sun's heating is less effective. Sometimes the air rises and is therefore cooled adiabatically, occasionally enough so that its moisture is partly condensed with a liberation of heat which still further warms the air. Gradually the heat escapes outward into space or downward to cooler earth and water until the air is no longer relatively warm. Then gravity pulls it down to the earth's surface where it awaits another warming the following day.

Group 2. Winds

12. Relatively cold air tends to sink, and crowd under warmer air, thus forcing it to rise. This is because cooling causes contraction and warming causes expansion, and hence a given volume of cold air is heavier than a like volume of warm, expanded air.

13. Winds always blow from places of higher air pressure to places of lower air pressure, because the great force producing winds is gravity.

14. Winds are deflected by the rotation of the earth; to the right in the northern hemisphere and to the left in the southern. The extent of deflection increases with latitude.

15. Winds blow at a large angle with the isobars if there is much friction and at a small angle if there is little friction. In other words, if there is little friction the air circulates round and round a center of low pressure, but where there is much friction it approaches the center of the low more directly.

16. Surface winds are influenced by topography and surface temperature. Winds tend to descend slopes, to follow valleys, to go toward warm areas, and to avoid elevations and cold areas.

17. Wind velocity depends on the barometric gradient, or difference in air pressure per horizontal unit, and upon the amount of friction; the steeper the gradient and the less the friction, the stronger the wind.

Group 3. Moisture

18. The ability of air (space) to hold moisture increases sharply with increased temperature, doubling with each increase of approximately 18°F. (10° C). In other words, as the temperature rises the relative humidity falls; this in spite of the fact that the absolute or actual humidity is increased with increased temperature whenever there is water which may be evaporated.

19. Atmospheric moisture is derived by evaporation from all moist surfaces, chief of which is the ocean.

20. The rate of evaporation increases with temperature and wind velocity, and with decreased relative humidity. It is also increased slightly by decrease in air pressure, in absolute humidity and in the salinity of the water.

21. Atmospheric moisture is transferred chiefly by wind and the vertical moving of air called convection. (Diffusion, the other process of transference, is altogether subordinate.)

22. Condensation occurs when moisture is cooled below the saturation point or dew point.

23. The amount of condensation depends upon the absolute humidity of the air, the amount of vapor cooled, and the extent of cooling beyond the dew point.

24. Precipitation occurs whenever drops, flakes or pellets are formed which are too heavy to be sustained in the air by the rising air currents.

25. Precipitation is heavy when a large volume of warm moist vapor is cooled notably below the saturation point.

As a summary of these laws of moisture, it may be well to describe the cycle that often occurs. The sun rises over the ocean and the air is warmed. It thereupon becomes able to hold more moisture and

evaporation is facilitated. As the air is blown over the moist surface, it takes up moisture, rapidly if it can hold much more than it already has, and slowly if it is nearly saturated. The wind blows upon the land carrying moisture from the ocean. It encounters a mountain range and is forced to rise. In doing so its temperature is lowered. At a moderate height it is cooled sufficiently so that it can no longer hold all its moisture and clouds form. At a higher elevation a drizzle is produced. If the range is high or if convectional overturning takes place, rain falls until the excess moisture has been precipitated.

CHAPTER II

LAWS CONCERNING THE HEATING AND COOLING OF THE EARTH

Distribution of Heat in Point of Time.

1. *Climate changes with the nature and effectiveness of solar radiation.*—This is true in so far as temperature and light are concerned, because the great source of heat on the surface of the earth is solar radiation, and also because the amount and type of solar radiation received and retained by the earth varies from time to time. The temperature of any place depends upon various factors, considered in subsequent laws, upon the amount and type of solar radiation and upon the amount of atmospheric and terrestrial absorption. None of these four factors operate at a constant rate in point of time or place. Geographic variations are discussed below. Widespread variations from time to time in the amounts of radiation and absorption are likewise a part of climate. The amount of radiant energy emitted by the sun also varies. A cycle of 11 or 12 years is recognized and there is evidence of both shorter and longer cycles, especially one of about 33 to 35 years.[2] Apparently there are other variations in the amount of energy emitted by the sun within periods of weeks or months.[3] In addition to variations in the amount of solar radiation, there is clear evidence of variation in the type of emanations, as is shown by the intermittent occurrence of auroral displays. Ultra-violet rays also do not always make up the same proportion of the emanations. Long term variations in either the amount or the kind of radiation reaching the earth, even though slight, undoubtedly affect climate in a fundamental way.[4] Sudden changes of pressure of a

[2]Marvin, C. F.: Theory and Use of the Periodocrite, *Mo. Weather Rev.*, Vol., 49, pp. 115-132, esp. p. 131, 1921; Clough, H. W., An approximate seven-year cycle in terrestrial weather with solar correlations, Ibid. Vol. 48, pp. 593-596, 1920, Henry A. J. Temperature Variations in the U. S. and Elsewhere, Ibid, Vol. 49, pp. 62-70, 1921; Huntington, E., Earth and Sun, 1923; Clayton, H. H., Solar Variation and Weather at Buenos Aires, *Smithsonian Misc. Collect.*, Vol. 71, 1920, and Helland-Hansen and Nansen, Temperature Variations in the North Atlantic Ocean and the Atmosphere, *Smithsonian Misc. Collect.*, Vol. 70, 1920.

[3]Abbot and others, The Solar Constant; *Mo. Weather Rev.*, Vol. 43, p. 212, 1915, and Vol. 47, pp. 1-3, 1919. Concerning the uncertainty of many of the daily variations in the Solar Constant, see Marvin, C. F., Forecasting the weather on short period solar variations, Ibid, Vol. 48, pp. 149-150, 1920.

[4]Huntington, E. The Solar Hypothesis of Climate, *Bull. Geol. Soc. Am.*, Vol. 25, 1914, pp. 477-577 and Earth and Sun, 1923; Brooks, C. E. P., The Secular Variations of Climate, *Geogr. Rev.*, Vol. 11, pp. 120-132, 1921.

remarkable type occur over extensive areas and may possibly be due to sudden variations in solar radiation.[5]

The amount of atmospheric absorption varies with the composition of the air. Changes in the water vapor, CO_2 and dust content of the air are particularly important as these are relatively active absorbers.[6] Water vapor is most important, being almost a full absorber for radiant energy sent out by a black body at a temperature of 212° F.[7] Nitrogen has no known absorptive power and oxygen absorbs only a few wave lengths other than those in the far ultraviolet.[8]

Variations in the amount of water vapor in the air are produced by changes in the temperature of the air and of evaporating surfaces, and in the distribution of land and water, and by variations in wind velocity. . Modifications in the distribution of land and water affect climate in many significant ways, but are geologic in origin and are produced slowly. Changes in the average temperature are produced by variations in insolation and in the composition of the air, and by changes in the surface of the earth, and thus in the amount of absorption and retention of radiant energy. It has been suggested that variations in the amount of CO_2 in the air have been due to differences in the temperature of the sea, in which much CO_2 is dissolved; to variations in the activity of volcanoes, which emit much CO_2; and to differences in the rate of depletion of the atmospheric CO_2 by coal-forming plants and by the carbonation of rocks. The rate of depletion is greater when the continents are elevated, as at present, than when they are low and partly

[5] Huntington, E., Solar Disturbances and Terrestrial Weather, *Mo. Weather Rev.*, Vol. 46, pp. 123-141, 168-177, 269-277, 1918.

[6] Fowle, F. E. Atmospheric Transparency for Radiation. *Mo. Weather Rev.*, Vol. 42, pp. 2-4, 1914 (a summary of earlier papers by Abbot and Fowle); Dines W. H. The amount of radiant energy absorbed and reflected by the earth and its atmosphere, *Quart. Journ. Royal Meteorol. Soc.*, April, 1917 (Abstracted in Meteorological Glossary, pp. 331-333; Humphreys, W. J., The Physics of the Air, 1920, (Volcanic dust receives especial consideration). The efficacy of CO_2 as an absorber is discussed in numerous papers. Chamberlin gives a good summary to 1906 in Chamberlin and Salisbury: Geology, Vol. 2, pp. 655-677. See also Clarke, F. W., The Data of Geochemistry, 4th ed., 1920. (*Bull.* 695, *U. S. Geol. Survey*), pp. 49-50, 141-145, and Huntington and Visher, Climatic Changes, their Nature and Causes, pp. 36ff, 19, 139, 1922; also, Kimball, H. H., Variations in the Solar Radiation in the U. S. *Mo. Weather Rev.*, Vol. 47, pp. 769-793, 1919. (The efficacy of water vapor as an absorber is especially emphasized in this comprehensive, detailed paper).

[7] Shaw and others, *Meteorological Glossary*, p. 33, 1918. In the Smithsonian Meteorological Tables, 1918, p. 231, the absorption of different wave-lengths is given. It varies irregularly from 6% to 100% for lengths given out by terrestrial radiation, but for most of the lengths it approaches 100%.

[8] Humphreys, Physics of the Air, p. 81, 1920.

submerged, as they have been at many times during geologic history.[9] Long-time oscillations in the amount of atmospheric dust accompany variations in explosive volcanic activity, and changes in the extent of dry land.[10]

Absorption by the earth's surface varies with the distribution of land and water, with the extent and type of soil, rock and vegetation and with cloudiness and the amount of snow-cover. All of these vary from time to time, and thus help produce climatic changes. The climate of any period, such as that of the present, is affected by all these complex influences, and by others mentioned below. As these conditions vary, climate changes. Climatology comprehensively studied is thus distinctly a dynamic subject instead of a static one.

DISTRIBUTION OF HEAT OVER THE EARTH.—*Effects of Latitude and Altitude.* 2. *Half of the earth is receiving heat from the sun at any given moment.*—Because of the rotation of the earth, there is a progressive change in the half which is heated by insolation. The amount of heat received per unit of time varies from a maximum in the area where the sun's rays are vertical to a minimum where they are tangent to the earth's surface.[11] Indeed at tangency there is almost no heating due to direct insolation because almost no energy is absorbed and only absorbed energy is effective in raising temperatures. At any given time the rays are nearly vertical (60° or more) over about one-fifteenth of the earth's surface. This proportion receives about 1.2 calories per square centimeter per minute on clear days from direct solar radiation.[12] It likewise receives radiation from atmospheric water and dust which have absorbed or reflect part of the solar radiation.[13] Indeed, in the

[9] Chamberlin and Salisbury, Geology, Vols. 2 and 3, 1906, as to variation in extent of lands. See also Willis, Salisbury and others, Outlines of Geologic History, 1910, and Schuchert, Paleogeography of North America, *Bull. Geol. Soc. Am.*, Vol. 20, pp. 427-606, 1910; and Pirsson and Schuchert, Textbook of Geology, Vol. 2, 1915.

[10] Schuchert, C., Climates of Geologic Time, pp. 265-298 of Huntington's, The Climatic Factor, *Carnegie Institution* Publ. 192, 1914, and (for Dust), Humphrey's loc. cit., pp. 569-603.

[11] The intensity of insolation varies with the sine of the sun's altitude. At the equinoxes, it varies as the cosine of the latitude. (Hann, J., Handbook of Climatology, Vol. 1 (tr. by Ward) p. 93, 1903.

[12] 63% of 1.92 calories, Abbot, Fowle and Aldrich, The Solar Constant of Radiation. *Mo. Weather Rev.*, Vol. 43, p. 212, 1915. "From March 10 to Sept. 10 the heat received from the sun and sky on clear days on each square meter of horizontal surface (at Washington, D. C.) is equivalent to the energy required to run twenty-five 40-watt electric lamps for 7 hours." (Kimball, H. H., Measurements of Radiation, Ibid, Vol. 43, p. 610, 1915.

[13] Dines, W. H., (*Quart. Journ. Royal Meteor. Soc.*, April 1917) estimates that the atmosphere absorbs nearly one-tenth as much solar radiation as does the earth

tropics, one-half of the total energy received is from diffused or reflected light.[14] The amounts of radiation (solar and atmospheric) received daily by the earth's surface vary notably with latitude, humidity, and seasons,[15] (See Law 8.)

3. *Normal temperatures decrease with increase in latitude, except just north of the equator, nearly 1° F. for each degree of latitude* (about 1° C. for each 2° of latitude) because insolation diminishes as the angle at which the sun's rays strike the surface of the spherical earth becomes smaller.[16] With this change there is greater reflection, an increase in the area over which a bundle of rays is spread, and of chief importance, an augmentation of the distance which the rays must travel in penetrating the atmosphere. Rays entering the atmosphere at a small angle often are reflected away from the earth. Penetration is also reduced by atmospheric absorption and diffraction or scattering of light rays.*

The average air temperature at the surface of the earth is about 59° F. (15° C.); near the equator it is 80° F. (27° C.) or above, except on the Pacific Ocean where it is about 77° F. (25° C.). The average along the tropics is about 74° F. (23° C.); in mid-latitudes it is perhaps 50° F. (10° C.), and in polar areas 10° F. (—12° C.) or less.[17]

In more detail, the mean temperatures are given as follows by Hann:[18] (The Fahrenheit equivalents are given just below the Centigrade figures.)

N. Pole	80°N.	70°N.	60°N.	50°N.	40°N.	30°N.	20°N.	10°N.	Equator
—20°C.	—17	—10	—1.2	5.8	14	20	25	27	26.6
—4°F.	1	14	30	42	59	68	77	81	80

10°S.	20°S.	30°S.	40°S.	50°S.	60°S.
26°C.	23	18	12	5	—1°C
79°F.	73	64	54	41	30

itself. It also absorbs nearly 3/4 of the radiation from the warmed earth and reflects back about 1/10. Only about 1/6 of the terrestrial radiation escapes to space directly.

*See Law 18 beyond.

14Hann, loc. cit., p. 81. See also Very, F. W., Atmospheric Radiation, *Bull. G., U. S. Weather Bureau*, 1900.

15Kimball, H. H., Variations in solar radiation in the U. S., *Mo. Weather Rev.*, Vol. 47, pp. 783-784, 1919.

16The variation of 1° F. per degree of latitude has been verified in the United States by A. D. Hopkins in his study of the flowering of plants. See "The Bioclimatic Law," *Mo. Weather Rev., Suppl.* 9, 1918 also *Scientific Monthly* 8, 495-513 1919 and *Mo. Weather Rev.*, Vol. 448, p. 355, 1920.

17These figures are from Bartholomew: Physical Atlas, Pt. 3, Meteorology, 1899, as are many similar figures below if not credited to some other source.

18Hann, loc. cit., pp. 200-202.

Were it not for the distribution of heat by winds and ocean currents, tropical temperatures would be much higher and polar temperatures much lower than now, possibly about 131° F. (55° C.) for the equator instead of 80° F. (26° C.) and —108° F. (—78° C.) for the poles, instead of about 0° F. (—18° C.) as now.[19]

The decrease in temperature with increase in latitude is not at a uniform rate. It is disturbed by variations in the proportions of land and water, highland and lowland, the amount of water vapor cloudiness and storminess in the different latitudes, and by differences in ocean currents. On the average the ocean is cooler than the land except in high latitudes where the reverse is true. According to Zenker marine climates are 8.5° C. (15° F.) colder than continental climates at the equator, 7.3° C. (13° F.) colder at latitude 20, 2.3° C. (4° F.) warmer at latitude 40, 8° C. (14° F.) warmer at latitude 60, and 14° C. (25° F.) warmer at latitude 70.[20] . Cloudiness generally lowers surface temperatures although it does not do so in winter in some cold regions.[21] Clouds in tropical latitudes reflect, on the average, more than half the solar radiation incident upon them.[22] Investigations in middle latitudes indicate that there is a reflection of 70%.[23] Nevertheless the climate of places in higher latitudes such as the British Isles, which receive much heat from the ocean, are kept mild in winter by being cloud-covered. In such places the effect of the clouds in retarding the escape of heat is more important in winter than is the lessening of insolation which they cause. Storminess increases upward convection, which in turn causes so much heat to be lost by radiation into space that stormy areas and belts tend to be abnormally cool, except in winter in high latitudes. This is in spite of the fact that the cloudiness associated with lows restricts the loss of heat, and the poleward blowing winds bring in much heat.[24]

---

19 Salisbury, R. D., Physiography, revised ed., p. 455, 1919.

20 Quoted by Hann, loc. cit., p. 212. In Die Lehrbuch der Meteorologie, 3rd ed., 1915, p. 153, Hann gives Lizmar's computations of the probable temperatures of land and water hemispheres at various latitudes.

21 For a good discussion of the lowering of temperatures produced by cloudiness in the lower latitudes (between 30′ N. and 30″ S.) See Huntington: *Bull. Geol. Soc. Am.* 1914, pp. 581-87. The influence of clouds on temperatures in northwestern Europe is discussed in Hann, loc. cit., p. 136.

22 Blair, W. R., *Mo. Weather Rev.*, Vol. 44, p. 194, 1916.

23 Balloon investigations carried on recently by the Smithsonian Institution in southern California, L. B. Aldrich, *Smithsonian Misc. Collect.*, Vol. 69, No. 10, Washington, 1919; Author's Summary reprinted in *Mo. Weather Rev.*, Vol. 47, p. 154, 1919.

24 Huntington, E., *Bull. Geol. Soc. Am.*, Vol. 25, pp. 572-574, 1914.

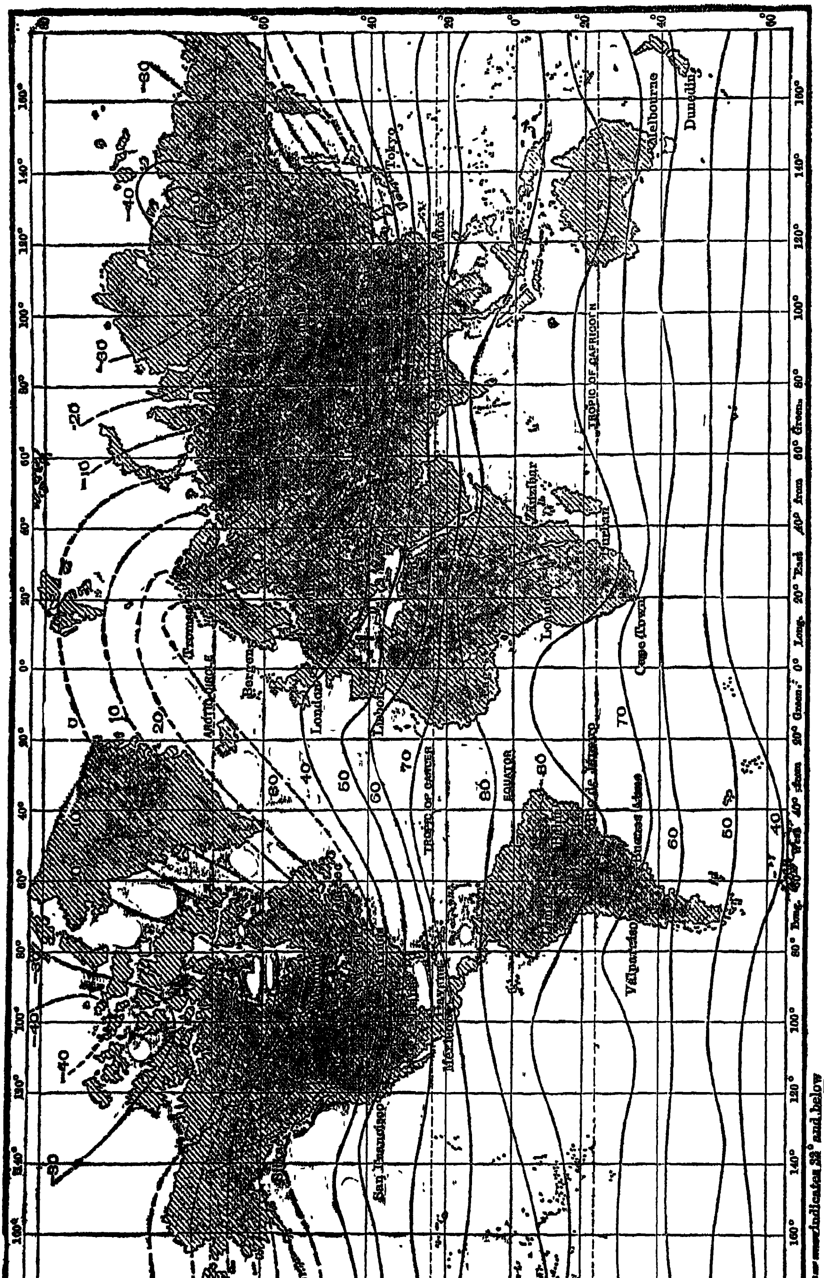


FIG. 1.—Mean Temperature During January. (From Huntington and Williams' Business Geography. Published by John Wiley & Sons, Inc.)

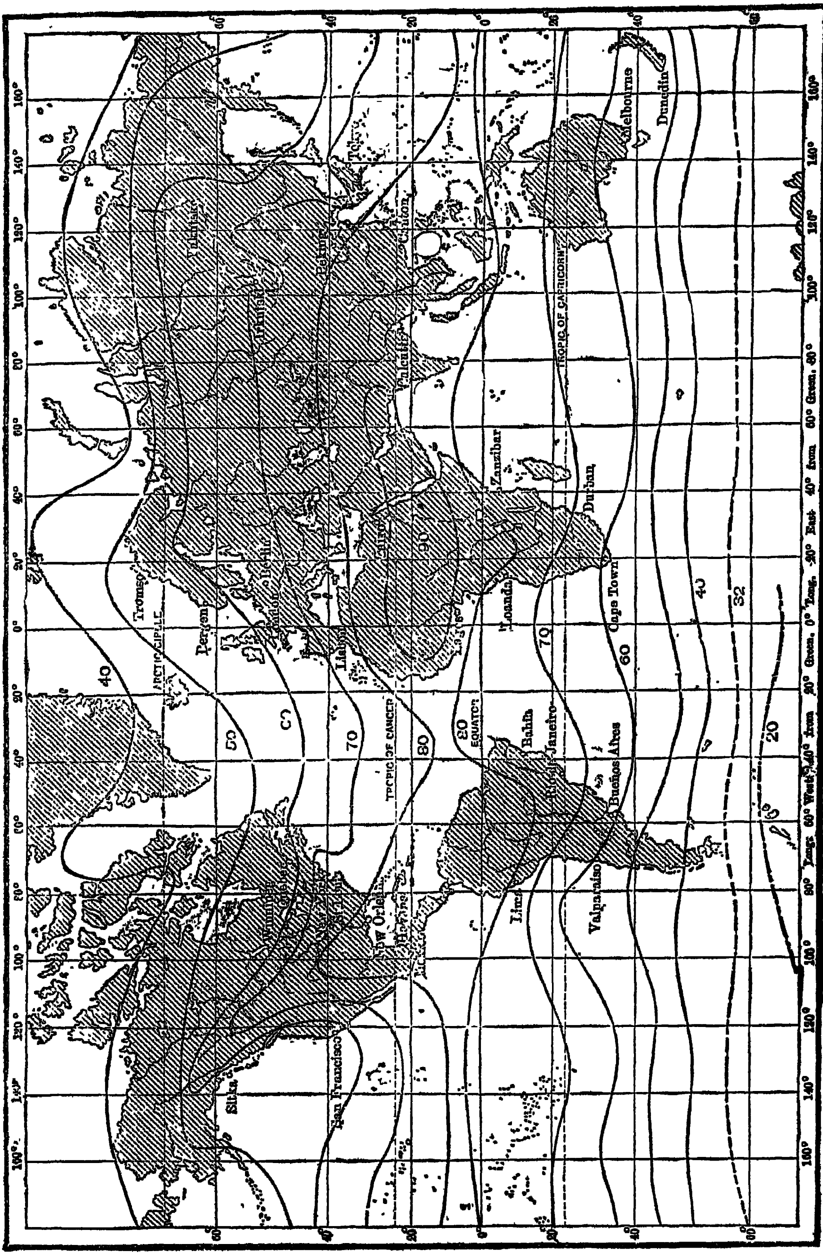


FIG. 2.—Mean Temperature During July. (From Huntington and Williams' Business Geography.)

4. *Normal temperatures fall with increase in altitude about 1° F. for each rise of 330 feet (1° C. for 600 ft. or 183 meters, or .6° C. for 100 meters).* The rate differs somewhat for mountains, plateaus and plains, being 1° F. for each 265 feet of ascent on mountains, 290 feet on plateaus, and 365 feet on plains (1° C. for each 180 meters on mountains, 200 meters on hills and 250 meters on plateaus).[25] For dry "free air" the decrease is 1° F. for each 300 feet (1° C. per 165 meters, or 6° C. per 1,000 meters), on the average, up to the base of the stratosphere, an elevation of about seven miles (11 km.).[26] At an elevation of about 2,000 feet (600 m.) above sea level, the effect of altitude on temperature is appreciable, and at 4,000 feet it is marked resulting in a short frost-free season in mid-latitudes. Lofty mountains, even in the tropics, have frigid temperatures at their summits, though not a polar climate. The normal decrease in temperature with increase in altitude is due partly to the increased distance from the chief source of atmospheric warmth, the warmed earth, but chiefly to the decreased absorption by the atmosphere of radiation from the sun and of radiation and conduction from the earth. The atmospheric substances which absorb radiation (water vapor, dust and CO_2) all decrease notably in amount with increase in altitude, and as has been remarked wherever there is little water vapor, CO_2 or dust, there is little absorption. Since radiant energy which is not absorbed does not raise air temperatures, high altitudes cool rapidly and become cold at night, and indeed even during the day, except where the sun is shining upon an absorbing surface. The thinness of the air, with the consequent fewer molecules to scatter the rays, also aids in the escape of heat.* The decrease in nocturnal temperature with increase in altitude is at a greater rate than the decrease in daytime temperatures. The decrease is also at a greater rate on the clear leeward sides of mountains than on the cloud-covered windward sides.[27] This disparity is due in part to the heat liberated at condensation on the windward slopes, and to the effects of foehns on leeward slopes. In the free-air, upward convection helps produce a progressive decline in temperature, since more heat is lost by expansion than is obtained by absorption or conduction. Furthermore, whenever convection is taking place, part of the air at any moderate altitude has recently arrived from a lower altitude. If

* See Law 17, beyond.

[25] Hann, Lehrbuch der Meteorologie, 3rd ed., p. 126, 1915.

[26] Humphreys, loc. cit., p. 38.

[27] Hann, Handbook of Climatology, Vol. 1, p. 249, 1903.

the rise is rapid, inertia may carry such air far beyond the level of equilibrium and so make it much colder than the surrounding air. However, this condition soon results in a settling of the comparatively dense abnormally cold air to a level where it is neither abnormally dense nor cold.[28]

Effects of Winds and Ocean Currents.

5. *Winds are important in affecting local temperatures, especially along coasts in the higher latitudes, and at night.* Windward coasts in high latitudes are on the average abnormally warm and leeward coasts abnormally cold. Much heat is carried from place to place over the surface of the earth by the winds. In winter many places in high latitudes frequently receive more heat from the wind than by insolation or from the radiation of heat stored up in soil or water. At night there is no insolation and on densely cloudy days in high latitudes, there is but little. When the surface of the ground is cold or snow-covered or the water is ice-covered, they give up only a little heat. The importance of the wind in high latitudes is suggested by the statement that from the poles to latitude 52° the earth's surface receives more heat from atmospheric radiation than by insolation.[29] Even when the sun is shining brightly, a locality may be cold if winds bring in a large body of cold air. Hence the direction of the surface winds often strongly influences the temperature at any place, especially in middle and high latitudes or near the coast.[30] For example, the northeastern part of the United States is remarkably warm in summer partly because southern winds prevail there, while the summers of northwestern Europe are kept comparatively cool by the northwesterly winds prevalent there at that season. Likewise the North Pacific coast of North America has abnormally cold summers partly because strong west or northwest winds from the cold northern Pacific Ocean prevail then.[31]

In the absence of surface air movement, there is little passage of heat by conduction from air to soil, rock or water or in the other direction, because stagnant air has a low thermal conductivity. This is one reason why the surface is hotter on a calm day than on a windy one and why the lower air is colder on a calm night than on a windy one.

[28] For further discussion of this explanation of the vertical decrease in temperature see Humphreys, W. J., A Bundle of Meteorological Paradoxes, *Journ, Wash. Acad. Sci.*, Vol. 10, pp. 153-171, 1920.

[29] Hann, loc. cit., p. 116.

[30] Hann, loc. cit., p. 70, states, "Few districts may be said to have their own climate" because of the importance of winds.

[31] Hann, loc. cit., p. 178.

On windy nights, air cooled by contact with cold ground is soon mixed with warmer air. Thus, although there is more cooling by conduction on a windy night than on a calm one because of the greater contrast between soil and air temperatures, a sufficiently greater quantity of air is involved so that the temperature of none of it becomes so low as that of the lower air on a calm night.

6. *Ocean currents help to warm windward coasts in high latitudes, and to cool those in low latitudes.*—Much heat is transferred by the movement of sea water. High latitude coasts are usually warmed by heat carried there by the oceanic circulation. Because of the influence of the wind, the agency which transfers the heat from the water to the land, this warming is chiefly felt on the windward coasts. Among the surface currents two may be mentioned: Winds from off the "Gulf Stream Drift" warm northwestern Europe 10° F. (5.5° C.) or more in midwinter.[32] Without its influence navigation would be interfered with by ice that would then accumulate occasionally even in the eastern ports of Great Britain. On the other hand, the Humboldt Current chills the coast of Peru and northern Chile. However, the upwelling cold oceanic waters there, as along other coasts in Trade Wind latitudes, is the chief cause of the coldness of such a current, rather than the rapid movement by the winds of cold water from high latitudes.[33] The active evaporation by the dry Trades is another cause of the coldness, both directly and also by making the surface layers more dense than the fresher but colder water below, which is crowded upward by the sinking of the denser surface water.

Possibly of more significance than surface currents is the deep-sea circulation. All the ocean is surprisingly cold, except the surface, because of the sinking and spread of cold water from high latitudes. The average temperature of the ocean, when all the depths are considered, is less than 40° F. (4° C.). In past geologic ages high latitudes have occasionally been much warmer and more equable than now. Indeed, magnolias and figs have grown in Greenland. If vast quantities of tropical heat were transferred poleward beneath the surface by a reversal of the deep sea circulation, some such mild climate would result.[34] Such a reversal might be produced by a notable increase in

[32] Salisbury, loc. cit., p. 470.

[33] Hann, loc. cit., pp. 185-187. See also Murray, J., The Ocean, 1912, and Brooks, C. F., Review of papers dealing with climates of Western coasts in the trade wind belt, *Geogr. Rev.*, Vol. 11, pp. 633-634, 1921.

[34] Chamberlin, T. C., On a possible reversal of deep-sea circulation, *Journ. of Geol.*, Vol. 14, pp. 363-373, 1906. See also Visher, S. S. *Bull. Geol. Soc. Am.*, Vol. 32, pp. 429-436, 1921.

the salinity of the ocean especially in low latitudes or by an increase in its temperature especially in high latitudes. The present surface currents from the tropics lose most of their heat by radiation and conduction to the air in low middle latitudes. However, surface currents may in times past have been more effective in transferring heat poleward than at present. Now, perhaps chiefly because of the retarding influence of cyclonic storms in mid-latitudes, the poleward movement of tropical waters is so slow that comparatively little heat reaches polar regions in this way.[35] If cyclonic storms were far less numerous than now the Westerlies would become more like the Trades in steadiness of direction, and the poleward movement of warm water would be much augmented, thus making possible mild polar climates where the distribution of land and water was favorable.[36] If during the past the deep sea circulation was of the "reversed" type at the same time that the Westerlies were steady at the surface, polar climates would have been especially mild.

7. *Windy places are commonly cooler than less windy ones otherwise similar* because: (1) Wind increases evaporation, and (2) increases the dispersal of local heat by conduction, except when the wind is extraordinarily hot. (3) Much surface wind has recently come from higher latitudes or altitudes and is cooler than the air it displaces. Wherever friction or topographic relations temporarily prevent wind, warm air accumulates whenever heating by insolation is greater than loss of heat by radiation. This is commonly the case in places which receive intense insolation but little heavier air (wind) to force the warm air to rise* There are three chief exceptions to this law: (1) Areas in middle and especially those in high latitudes are often warmed by wind from the open ocean in winter or from the direction of the equator; hence windy places in high latitudes are often warmer than calm places. (2) Depressions are often cooler during calm nights than on windy ones, because cold air accumulates in depressions during calm nights.† (3) Many places are occasionally warmed by foehn winds.

---

* See Law 18, beyond.

† Similarly snow-covered surfaces are often cooler on calm nights than on windy ones partly because stagnant air in contact with cold snow cools to a lower temperature than that reached by a mixture of surface air and the warmer air of moderate altitudes such as obtains on windy nights.

35 Helland, Hansen and Nansen, Temperatures of the North Atlantic, *Smithsonian Misc. Collect.*, Vol. 70, #2537, 1920. Huntington and Visher, Climatic Changes, their Nature and Causes, pp. 174-176, 1922.

36 Huntington and Visher, loc. cit., pp. 166-187.

Effects of Earth's Rotation, Shape and Inclination.

8. *Seasons of temperature occur in middle and high latitudes,* because of the revolution of the earth about the sun and the constant inclination of its axis to the plane of its orbit. As the axis maintains a practically constant direction in space at an angle of about 23½° to the ecliptic, the northern hemisphere is tipped toward the sun at one time, and six months later, when the earth is in the other side of the orbit, it is tipped away from the sun. The hemisphere tipped toward the sun receives more vertical and nearly vertical rays than the other and hence is warmer. In other words, the north-south shifting of the zone of greatest insolation accompanying the revolution of the inclined earth produces most of our changes of seasons. For example, in the United States, Minnesota receives six times as much radiation per unit area on June 21 as on December 21, and Louisiana two and one-half times as much on June 21 as on December 21. During a year a unit area in Louisiana receives 7 per cent more radiation than one in Minnesota, receiving 36 per cent more in the colder six months but 11 per cent less in the warmer three months. In July, Minnesota receives 20 per cent more than Louisiana. The arid southwest receives almost twice as much radiation as the northeast in winter and nearly 25 per cent more in summer. For example, South Carolina receives only about 75 per cent as much radiation per unit area in a year as does more sunny New Mexico. New Mexico leads each month in the year but more in the colder months and in July than in the other months, because of cloudiness in South Carolina then. The highest average amount received in gram calories per minute per square centimeter is 700 on June 21 in the arid southwest. The lowest is a little less than 100 on December 21 along the northern border and in the Great Lakes region.[37]

Although the earth is nearer the sun and receiving one-fifteenth more insolation in January than in July, the Southern Hemisphere does not receive a greater amount of heat in a year than the Northern. The earth moves with a sufficiently greater velocity along its orbit when nearest the sun as compared with its velocity when farthest away (in July), so that it receives as much heat when it is more than the average distance from the sun as it does when it is less than the average.[38] Indeed, the temperature of the earth as a whole increases from January to July nearly 2.7° F. (1.5° C.) while its distance from the sun is increasing. This is chiefly because of the greater land area in the Northern Hemisphere.[39]

[37] Kimball, H. H., cited in note 15,

[38] Hann, loc. cit., pp. 93-101,

[39] Ibid, p. 201.

Seasonal changes of temperature have been far less extreme during most of the better known epochs of the geologic past than they are at present. Indeed, freezing temperatures apparently did not prevail even in moderately high latitudes, at least not along the coasts, except during the several colder or Glacial periods.[40] Students of celestial mechanics insist that there has been no great change in the position or inclination of the earth's axis since the present solar system was organized. It is altogether unlikely that the higher latitudes could have been warmed sufficiently by the escape of heat from the interior of the earth to compensate for the lack of direct insolation in winter. Leading geologists estimate that the earth's interior probably is about as hot now as formerly.* Yet today the escape of heat is normally negligible.[41] In ancient times when high latitudes had a mild climate they must have received the necessary heat through the agency of atmospheric or oceanic circulation. A general "planetary" circulation of the atmosphere like that of the present seems called for by the distribution of insolation. A change in the oceanic circulation appears much more likely than many of the other changes hypothecated. If the ocean were distinctly warm in high latitudes, seasonal changes would be much lessened. The change in the temperature of the ocean might be due to a change in the amount of heat received from the sun or to a change in the amount of heat held in by the atmosphere. The amount held would fluctuate with the composition of the air, with storminess, and with the extent of land and water. Chamberlin[42] has developed the hypothesis advanced earlier by Tyndal, Arrhenius and others, that the alternation of glacial periods and warm climates in high latitudes is chiefly due to fluctuations in the CO_2 content of the air and to accompanying fluctuations of the moisture content. More atmospheric CO_2 would mean a somewhat greater retention of heat and thus more water vapor accompanied by a further increase in heat retention. Huntington[43] reports evidence

*Chamberlin, T. C., personal communication.

40Barrell, Joseph: Rhythms and the Measurement of Geologic Time, *Bull. Geol. Soc. Am.*, Vol. 28, pp. 745-904, 1917; citation on p. 827. Schuchert, C.; Climates of Geologic Time in the *Climatic Factor*, pp. 265-298, 1914, Reprinted in *Smithsonian Annual Report*, 1914.

41The mean temperature of the earth's soil is estimated by Trabert to be raised by conduction from the internal heat of the earth by the trifling amount of 0.1°C. Bowman: Forest Physiography, p. 60, 1911.

42 Briefly stated in Chamberlin and Salisbury: Geology, Vol. 2, pp. 665-667; Vol. 3, pp. 433-436, 1906. However see Clarke: Data of Geochemistry, 4th ed., pp. 142-145, 1920.

43 Huntington: *The Climatic Factor*, Carnegie Institution, 1914; and The Solar Hypothesis, *Bull. Geol. Soc. Am.*, Vol. 25, 1914, pp. 477-577. Fuller evidence is presented in Climatic Changes, 1922 and in Earth and Sun, 1923.

of a change in storminess and in the location of storm tracks, and points out that heat retention would alter with storminess. Both Chamberlin and Huntington consider modifications in the distribution of land and water important contributory factors. Chamberlin considers the reversed deep-sea circulation, mentioned above, as the probable source of much of the extra warmth present in high latitudes during the mild periods of the past. This reversal he attributes in part to the influence of increased CO_2 in the air with its resultant greater retention of heat, and hence higher oceanic temperatures. Several other agencies have been suspected of being important in producing climatic changes.[44]

9. *The rotation of the earth is such that nearly all parts are lighted and heated by solar radiation for approximately twelve hours and then have darkness for a similar period.* High latitudes, and especially the polar regions (one-twelfth of the globe), are partial exceptions to this rule, as are mid-latitudes near the solstices.[45] However, the oblique angle at which the sun's rays penetrate the atmosphere and strike the surface in high latitudes prevents such excessive heating as would result in low latitudes if the period of heating there were much longer than it is. If the days were 16 hours long in low latitudes, life of the present sort probably would be impossible in the drier regions because protoplasm would be killed by the high temperature. In all latitudes, the coldest normal temperatures occur about sunrise, and the warmest, sometime after mid-day.[46]

10. *Because of the spheroidal shape of the earth and the inclination of the axis, days and nights vary significantly in length in middle and*

---

44 See Humphreys: The Factors of Climatic Control; *Physics of the Air*, pp. 556-630. Humphreys advocates the efficacy of atmospheric dust. Ekholm, N., (On the variations of the climate of the geological and historical past and their causes, *Quart. Journ. Royal Meteorol. Soc.*, 1901, pp. 1-61) considers variations in the obliquity of the earth's orbit as an important influence supplementing variation in the amount of CO_2. Several writers have considered variations in the distribution and height of the land as the chief and direct cause of the changes of climate. (See Harmer, Influence of winds upon the climate of the Pleistocene, *Quart. Journ. Royal Meteorol. Soc.*, Vol. 27, pp. 303-305, 1901. (Summary), and Clarke, Data of Geochemistry, loc. cit., and Brooks, C. E. P.: Continentality and Temperature. *Quart. Journ. Royal Meteorol. Soc.*, April 1917, and Oct. 1918 (30 pp.), Schuchert, loc. cit., discusses the chief hypotheses advanced before 1914; and Huntington and Visher, Climatic Changes, 1922, all the more important hypotheses.

45 For the length of day in each latitude and for each day in the year see *Smithsonian Meteorol. Tables*, Washington, 1918.

46 Meissner reports, *Mo. Weather Rev.*, Vol. 48, p. 39, 1920 that the minimum comes 30 minutes after sunrise from May-September; 15 minutes after during spring and fall; and 10 minutes before in winter.

high latitudes.—They are always the same at the equator and nearly the same to about latitude 20.[47] The disparity increases with the latitude. In July (northern hemisphere) the days average 13.9 hours in length at latitude 30; 14.7 hours in length at latitude 40; 16 hours at latitude 50; 18.1 hours at latitude 60; and 21 hours at latitude 65.[48] Long days make summer warmer and long nights make winter colder than they would be if days and nights were always equal. The long summer days of high latitudes permit the growing of crops in extensive areas where those crops could not be grown if the days and nights were equal in length throughout the year (as they are at the equinoxes). Only at the poles is there six months of continuous day or night. All parts of the earth are lighted during one-half of the year.[49]

Effects of Character of Surface.

11. *Land is notably warmer than water in summer and cooler in winter. Land is usually warmer than water by day except in winter in the higher latitudes.*—Water becomes warm less quickly than land and retains heat longer.[50] The ocean thus is a great reservoir of heat in autumn and early winter.[51] In spring and summer it takes up heat from the air which it returns in autumn and winter. The ocean therefore notably affects the temperature of adjacent lands toward which the winds blow. Seas and large lakes act similarly until frozen over.[52]

---

47 Salisbury, loc. cit., p. 426.

48 Abbe, C., Relations between Climates and Crops, pp. 102-103, *Weather Bur. Bull.*, #36, 1905, for latitudes to 40°. For all latitudes see *Smithsonian Meteorol. Tables*, 1918, pp. 203-214.

49 Not exactly; there are fewer long nights than long days, in the northern hemisphere, and the opposite in the southern hemisphere. This is due to the earth's elliptical orbit and its greater velocity of revolution when near the sun than when far away. Furthermore all parts of the earth receive sunlight for slightly more than half of the year because of the reflective effects of the atmosphere. The sun is visible when it is about 1° below the horizon. Hence in a year there are about 2/360 more hours of light than of darkness (Humphreys, W. J.: A Bundle of Meteorol. Paradoxes, *Journ. Wash. Acad. Sci.*, Vol. 10, pp. 168-170, 1921.)

50 Several reasons why water heats and cools more slowly than land are given in Salisbury, Physiography, pp. 454-455, and in Ward, Climate, pp. 36-37.

51 Pettersson: Meteorological Aspects of Oceanography, *Mo. Weather Rev.*, Vol. 44, pp. 338-341, 1916; and Brooks, C. E. P., cited in note 44 (Abstracted in *Mo. Weather Rev.*, Vol. 47, pp. 653-654, 1919.)

52 The ice will not be as cold as the air above it when that air is very cold, because of the tempering influence of the relatively warm water beneath the ice. Ice however is a very poor conductor of heat; hence ice-covered water bodies contribute heat to the atmosphere so slowly as to have little influence as a source of heat. See, Birge, E. A., Heat Budgets of American and European Lakes, *Transac. Wis. Acad. of Sci., Arts and Letters*, Vol. 18, pt. 1, 47 pp., 1914.

For example, the North Sea often raises the temperature of cold winds blowing from the continent to England as much as 18° F. (10° C.). Lake Ontario and the other Great Lakes likewise often warm cold winds several degrees centigrade.[53] Other effects of unequal heating of land and water are land and sea breezes and monsoon winds. Because the ocean is cooler than the land more than half the time, average temperatures are lower along the coast than inland, except in the higher latitudes. "The heat equator" is north of the rotational equator except near Australia because there is more land in low latitudes in the northern hemisphere than in the southern. The greater extent of arid land north of the equator is of especial significance because arid lands are much warmer than the ocean in low latitudes. It is chiefly for this reason that the northern half of the eastern hemisphere averages 4.5° F. (2.5° C.) warmer than the southern half, and the eastern hemisphere 1.8° (1° C.) warmer than the western.[54] In the higher latitudes, the ocean is warmer than the land, especially in winter. For example in Europe between latitudes 47° and 52°, for each 10° of longitude farther from the west coast there is a decrease of 2.4° F. (1.3° C.) in mean temperature and a decrease of 5.6° F. (3.1° C.) in winter, but an increase of 1.3° F. (0.7° C.) in summer.[55]

12. *Snow or ice-covered areas are notably colder than similar areas not so covered except those immediately to leeward,* chiefly because air temperatures much above the freezing point will not occur where snow or ice is widespread. After a temperature of 32° F. (0° C.) has been attained, additional heat received by the surface air usually melts the ice, and becomes latent energy instead of raising air temperatures. Furthermore, the reflection from snow or ice lessens the effectiveness of solar radiation greatly, 40 per cent or even as much as 70 per cent, according to Abbot. A third factor reducing the temperature of snow-covered areas is the evaporation from the snow. Likewise the snow mantle is a good non-conductor and also a poor absorber of heat, and therefore interferes with the warming of the air by heat in the soil. These influences, together with the general dryness of the air in clear weather, often lead to low nocturnal temperatures over snowfields in clear weather.

13. *The vegetal cover affects temperature conditions.*—In forests the air is cooler by day and warmer by night, on the average, than in

[53] Hann, loc. cit., pp. 179, 180.
[54] Hann, loc. cit., p. 202.
[55] Ibid, p. 138.

grasslands, and in other places possessing scanty vegetation. Vegetation absorbs much radiation and reflects some also. Likewise it interferes bodily with the escape of heat from below, which effect is especially prominent at night. Another important way in which vegetation modifies temperatures is in promoting evaporation, a cooling process. It is largely because of the greater evaporating surface which the leaves afford that the temperatures in dense equatorial forests average less than those at coastal stations.[56] Additional effects of vegetation on temperatures are given under other laws.*

14. *Diurnal and seasonal lag usually increases with latitude, at least in middle latitudes, and decreases with increased aridity.*—Lag is due to the fact that heating is delayed by the presence of ice, cold water, frozen or chilled soil and rock and that cooling is delayed by stored-up heat in water, rock, soil and water-vapor. There is less lag for atmospheric temperatures in arid regions than in humid regions because: (1) There are fewer clouds and less other atmospheric moisture to interfere with radiation; (2) there is little water vapor available for evaporation or freezing; (3) there is a greater exchange of heat by conduction between the atmosphere and the land because the scanty vegetal cover is less effective than the denser vegetation of more humid lands in maintaining a layer of stagnant air between the land and the atmosphere. Another cause of more effective conduction in arid regions is the greater exposure of firm rock there than in humid regions. Rock is a much better conductor than soil.[57] Air over the water reaches its maximum temperature sooner after the time of maximum heating than air over land (about 1 P. M., instead of about 2 P. M.).[58] This is largely because, (1) water heats and cools so slowly that it has only a small diurnal range and hence little positive effect on the diurnal temperature of the air. Thus over the water air temperatures cease to rise almost as soon as insolation decreases. The temperature of the surface of the land is usually higher than that of the air for some time after noon, so that radiation and conduction from it continue to raise the temperature of the air. (2) Since water is a better reflector than land, the decrease in the angle of incidence after noon soon means a much greater reflection from water than from land with a correspondingly greater decrease in effective insolation per unit area on the water (3) Increased evaporation with higher temperatures also tends to pre-

* See Laws 14, 17, 19 and 23.

[56] Ibid, p. 138.

[57] Patten, H. E., Heat transference in Soils, *U. S. Bur. of Soils, Bull.* 259, p. 49, 1909.

[58] Hann, *loc. cit.*, p. 13.

vent a further rise in water temperatures.[59] In the intermediate zones the amount of seasonal lag averages about a month, but increases with latitude chiefly because of the corresponding increase in the amount of surface water, snow, and ice.

The lag is greater in water than in air and is still greater at moderate depths in the soil. Unless shallow, water is commonly warmest an hour or two before sundown, and two or even three months after the summer solstice. It is coldest an hour or two after sunrise, and two or three months after the winter solstice. The vertical circulation, and hence the amount of lag, is affected, however, by the salinity where average water temperatures are near 39° F. (4° C.), as fresh water is densest at 39° F. (4° C.), while oceanic salt water is densest at 28° F. (2° C.). Depth and heating being equal, the lag is greater in fresh than in saline water. The lag in soil varies with depth. At the greatest depth commonly reached by the diurnal change of temperature (about two to three feet, depending on the kind of soil and on the extent of the atmospheric diurnal range), the highest temperature is at night and the lowest by day. The seasonal change is normally inappreciable below 35 to 70 feet (11-12 meters), even in regions of great seasonal range, and is much less than 35 feet in the tropics with their small seasonal range of temperature, and in polar regions with their frozen subsoil.[60] Near the bottom of the zone of seasonal change in temperature in the soil wherever that zone is deep, the maxima usually occur about five months later than they do in the air above.

RANGE IN TEMPERATURE.—*Diurnal Range.*

15. *Diurnal range in temperature is greatest, other things being equal, where and when day and night are of equal length. Hence it normally decreases with increase in latitude, except near the equinoxes, when the reverse is true.*—When nights are much shorter than days nocturnal cooling does not last long enough to reduce the temperature so much as when nights are longer. On the other hand short days seldom become warm enough to produce a marked diurnal range. Near the equinoxes, diurnal range tends to increase with latitude, because the decrease in absolute humidity characteristic of increase in latitude allows more rapid heating and cooling in higher latitudes than in lower

---

[59] Only a fraction of the heat entering open water raises its temperature; the rest causes evaporation. The fraction used for evaporation rises rapidly with increased temperature of the water and is very high in tropical seas. (Hann, loc. cit., p. 131). In northern United States and northern Europe, however, according to Birge, E. A., *Trans. Wisc. Acad. Sci.*, Vol. 18, 1914, more of the heat is used to raise the temperature than to evaporate the water.

[60] Bowman, I., Forest Physiography, p. 60, 1911.

latitudes. These normal relationships between daily range and latitude are interfered with in the cyclonic storm belts because intense storms occasionally increase daily range notably. Furthermore, three influences locally interfere with the normal seasonal occurrence of the greatest ranges. Instead of coming at the equinoxes, some places have a greater average range in winter, because of augmented storminess at that season, with resulting occasional sharp temperature changes within 24 hours. Places with dry seasons often have the greatest ranges in the dry months since aridity favors a wide range. (See Law 17, beyond.) Finally, seasonal changes in wind direction give some places near coasts a smaller range at one season than at another. (See following law.)

16. *Diurnal range in temperature increases with decrease in the influence of the ocean or of lakes* as water tends to prevent the temperature from rising notably by day and from falling low at night. The average diurnal range in the surface waters of the ocean varies from 2-5° F. (1.1°-2.8° C.).[61] On the other hand, the average diurnal range over the land is more than 12° F. (7° C.) and the temperature of the surface soil or rock is often several degrees colder or warmer than that of the air a few feet above. The air over water is kept warm at night in three ways: (1) The large amount of heat given up by the water, due to its high specific heat. (2) The vertical movements, by which warmer and hence less dense water from below replaces the partially cooled surface water. (3) The abundance of atmospheric moisture and the frequent cloudiness above water bodies checks the loss of heat by radiation at night.

17. *Diurnal range in temperature increases with aridity, on the average.*—A large range is less common in humid than in arid regions because humid regions have more atmospheric moisture, greater cloudiness, more evaporation, more condensation, more dense vegetation and more moist soil. In humid regions atmospheric moisture greatly hinders surface absorption and loss of surface heat by radiation, and in addition clouds often check insolation by day and loss of heat by radiation at night. Furthermore, in moist areas much heat is used during the day to evaporate water. This latent energy is returned to the air as heat when condensation takes place, as when dew is formed at night. The greatly increased evaporation at higher temperatures is an important factor in preventing temperatures from rising much above 100° F. (38° C.) in moist regions. Twice as much moisture can be contained

[61] Ward, R. De C., Climate, p. 37; quoting from Challenger Report. For an excellent summary see: Buchan, Alex., Meteorological Results of Challenger Expedition, *Proceed. Royal Geogr. Soc.*, Vol. 13, pp. 137-156, 1891.

in a given space at 108° F. (42° C.) as at 90° F. (32° C.). The formation of fog and clouds at night often prevents frost by liberating heat in condensation as well as by checking the loss of heat by radiation. The influence of cloudiness on nocturnal cooling is well illustrated by data reported by Hellman.[62] On a clear night in Germany, the average temperature one-half meter above the surface is 6.7° F. (3.7° C.) higher than at the surface, while with an overcast sky there is no difference. Furthermore, when the sky is one-tenth overcast the temperature contrast is one-tenth less than on a clear night. Dew formation with its notable release of latent heat of vaporization is also often significant in preventing low temperatures. Sometimes it prevents frost. Indeed, the lower the relative humidity at 8 P. M., the greater is the expected cooling by morning.[63] The influence of vegetation and soil in affecting conduction has been mentioned. (Law 14.)

Even in deserts certain influences prevent excessively high air temperatures by day: (1) The loss of heat by radiation is rapid because of low humidity and slight cloudiness; (2) the rate of radiation increases rapidly with increases in temperature (varying as the fourth power of the absolute temperature for black bodies—Stefan's Law); (3) conduction of heat into the earth is favored by the abundance of bare rock; (4) the prevalent convectional winds by day carry much heat aloft; (5) the increased dustiness induced by the high winds and whirlwinds checks insolation. These five influences and the shortness of the days, usually prevent the occurrence of temperatures higher than about 120° F. (50° C.). Low temperatures at night are delayed, not prevented, by the dust because most dust in deserts is coarse and low and much of it settles during the prevailingly calm nights. Furthermore the dust radiates heat readily and before morning is colder than the surrounding air, which it then helps to cool by conduction. Whereas the daily range in air temperature in humid areas is often less than 10° F. (5.6° C.) and commonly less than 20° F. (11° C.), in warm deserts it is usually more than 30° F. (16° C.), often more than 50° F. (28° C.), and not rarely 70° F. (39° C.). Indeed dark-colored rocks in the Sahara often experience a diurnal range of nearly 176° F. (80° C.).[64]

18. *Diurnal range in temperature increases with altitude up to the snow-line for places similarly exposed, except on some valley slopes.*—

[62] *Mo. Weather Rev.*, Vol. 48, p. 38, 1920

[63] Hann, loc. cit., p. 145. For a much fuller discussion of this point see Smith, J. Warren,: Predicting minimum temperatures from Hygrometric Data, *Mo. Weather Rev.*, Supplement, No. 16, 1920.

[64] Hann, loc. cit. p. 147, quoting Walther.

This is because at higher altitudes there is progressively less air, less water vapor, less CO_2 and less dust. Decrease in these latter substances is significant because together they absorb nearly all of the radiant energy absorbed by the air.[65] Air pressure is significant in this connection because molecules of all gases scatter or diffract an important fraction of solar radiation.[66] Above an elevation of two miles (3 km.) the scattering is chiefly molecular. Below that level, dust is important.[67] Scattering interferes with the passage of radiant energy. Hence, because of lessened atmospheric absorption and lessened diffraction, a larger fraction of solar radiation is available at high than at low altitudes for daytime warming of favorably exposed surfaces. For the same reasons the loss of heat by radiation is very rapid at night, and by day from places in the shade. Certain conditions at high altitudes are adverse to large diurnal range, but are not sufficient to prevent a general increase in range with increase in altitude.[68] For example: (1) In spite of the frequently large ranges of temperature of favorably exposed rocks, air temperatures are slightly affected because the air normally passes too rapidly, because of the strong winds, to be affected appreciably by conduction or radiation from or to the small rock surface. (2) The "down drainage" of cool, heavy air at night often results in valleys being cooler than adjacent heights of moderate elevation. The cool air moves outward from the hillside and slightly downward as the colder air lower in the valley settles. It is replaced by somewhat warmer air from greater distances from the cold surface. The accumulation of cold air in valley bottoms results in the zone of highest temperatures being found some distance up on the valley sides, though below the normally colder hilltops and peaks. Such warmer zones are sometimes "frost free" in the fruit-growing season.[69] In free-air the diurnal range decreases with height. There is often a difference of 5° F. (3° C.) between the surface temperature and that

[65] According to Ganot's Physics, (p. 630) CO_2 has 90 times the absorption power of ordinary air, and water vapor has 70 times the absorption power of dry air. For a fuller discussion of this subject, however, see Humphreys, Physics of the Air, pp. 88, 606-608, 1920.

[66] Abbot, Fowle and Aldrich, *Proceedings Nat'l Acad. of Sci.*, June 15, 1915, pp. 331-33, and, more fully, in *Annals of the Astrophysical Observatory, Smithsonian Institution*, Vol. 3.

[67] Angstrom, A., Scattered radiation from the sky, *Mo. Weather Rev.*, Vol. 47, p. 797, 1919.

[68] Hann, loc. cit., p. 238.

[69] See Cox, H. J., Thermal belts in the North Carolina Mountain Region, and their Relation to Fruit Growing, *Annals Assoc. Am. Geographers*, Vol. 10, pp. 57-68, 1920.

of the air five feet (1½ meters) above, and sometimes in dry areas there is a difference of 14° F. (8° C.)[70] This is because air is a much poorer radiator than soil or rock.

19. *Diurnal range in temperature increases with decrease in vegetation:* (1) Bare soil or rock, especially if dark-colored, as it commonly is, absorbs more radiation than do most plant-covered areas. There is much reflection from leaves, many of which are light-colored and most of which are somewhat shiny. (2) There is more evaporation from vegetation than from the average soil or rock-covered area. (3) A small part of the energy absorbed by plants is used in photosynthesis becoming latent in carbohydrates. (4) Vegetation hinders the escape of heat from the soil, and from the entrapped air, especially at night and thus delays cooling sufficiently to prevent minima so low as those reached in bare areas, or in the air above the vegetation. The escape of heat is reduced by the absorption of radiation from the soil by the subaerial parts of the plants and the subsequent return of part of this energy to the earth by downward radiation. The greater humidity of the air near plants as compared with more remote air acts in the same way. Furthermore, vegetation interferes bodily with convection. The way in which vegetation decreases the loss of heat at night by conduction has been mentioned in Law 13. Because of these influences the diurnal range in forests averages several degrees less than in adjacent fields.[71] However, when deciduous trees leaf-out in spring, frost is perhaps sometimes induced by the sudden increase in evaporation.[72]

20. *Diurnal range in temperature differs with differences of slope.*—A slope inclined toward the noonday sun is heated more during the day than one not so inclined but both cool to nearly the same temperature by morning. Steep slopes usually have less range than gentle slopes equally well situated in respect to insolation, because on steep slopes warm air is more quickly removed by upward convection during the day, and cold air by drainage downward at night and thus the temperature of the surface on steep slopes is more nearly equal that of the free-air, than is the case with gentle slopes.

Interdiurnal Variability.

21. *Interdiurnal temperature variability increases with latitude up to subpolar latitudes if other conditions are equal.*—In tropical latitudes nearly all days have similar temperatures, as do the nights. In high

[70] Hann, loc. cit., p. 42.

[71] Fernow, Abbe, and others, Forest Influences, *Bull.* 7, *Forest Service, U. S. Dept. of Agri.*, 197 pp., 1893.

[72] Mayer, A. G., Radiation and absorption of heat by leaves, *Am. Jour. Sci.*, 3rd series, Vol. 145, pp. 340-346, 1893.

latitudes there is great contrast among both the days and the nights. This variation is the result of: (1) Increased disparity in the length of day and night with increase in latitude; (2) the fact that in middle and high latitudes, wind direction is much more significant in changing local temperatures than in low latitudes, where almost all winds are warm; (3) storms also increase the variability, and storms apparently increase in frequency and intensity, on the average, with latitude to subpolar latitudes. One of the ways in which storms cause this variability is in producing interdiurnal changes in cloudiness.

Seasonal Range. 22. *Annual or seasonal range in temperature increases with latitude to the region of persistent snow and ice* because of the increased significance of the changes in the angle of insolation and the increased contrast in length of day and night. Long days in summer tend to produce high maxima. Long nights in winter tend to produce low minima. There is a rapid lowering of minima with increase in latitude and a less rapid lowering of maxima. As minus departures from the normal temperature are usually greater, and often twice as great as the plus departures, low minima are more important than high maxima in producing great seasonal range. The regions of extreme range are therefore on the continents in high latitudes where the winters are long but where snow does not persist throughout the year and thus prevent high maxima; *i. e.*, in the interiors of Northern Asia (range 170° F.; 94° C.), and in northern North America (range 160° F.; 89° C.). The extreme range in the Sahara is only 90° F. (50° C.). Near the equator the average annual range, based on monthly means is 5° F. (3° C.) or less; for latitude 20, about 13° F. (7° C.); for latitude 30, about 18° F. (10° C.); for latitude 40, about 26° F. (13° C.); and for latitude 50, about 46° F. (25° C.).[73] The average annual range for the land based on extreme maxima and minima is about 40° F. (22° C.) near the equator, about 80° F. (44° C.), in latitude 30, and about 120° F. (67° C.) in latitude 60.[74]

23. *Annual or seasonal range in temperature becomes greater with decreases in the influence of the oceans, in the amount of moisture present in the air, soil or on the surface, and with reduction in vegetation,* because conditions favorable for high temperatures by day, favor high summer averages and maxima, and conditions favorable for low temperatures at night favor low winter averages and minima. (See Diurnal range, Laws 15-20 for reasons.) Marine climates have little range compared with continental climates. The average annual range

[73] Supan, quoted by Hann, loc. cit., p. 135.

[74] From Bartholomew's Charts, loc. cit.

in marine climates is 15° F. (8.3° C.) for latitude 35 N., and 14.8° F. (8.2° C.) for latitude 60. For continental climates, latitude 40 has a range of 52° F. (29.5° C.), and latitude 60 a range of 88° F. (48.6° C.). The mean for these different latitudes gives the range for marine climates as 14.8° F. (8.2° C.), while that of the continental climates is 70° F. (39° C.), or nearly five times as great.[75] The contrast between continental and marine climates is on the average less in latitudes 0-40 than in higher latitudes, because annual range decreases with latitude. Nevertheless it remains notable.

American examples of seasonal range follow:[76] Western Oregon has a normal seasonal range of only about 18° F. (10° C.), while South Dakota has a range of 60° F. (33° C.). The extreme ranges for these places are about 85° F. (46° C.) and 165° F. (91° C.), respectively Because of the increased dominance of continental conditions, seasonal range commonly increases toward the east on land areas in the westerly wind belt, although the eastward increase in humidity, as in the eastern United States, tends to counteract this influence. Examples of the increase in range toward the east are: Southwestern Arizona has a monthly range of 30° F. (17° C.) and Northwestern Georgia, one of 35° F. (19° C.) the extreme ranges at Yuma, Ariz., and Columbus, Ga., are 100° F. (55° C.) and 112° F. (62° C.), respectively. Nevada has a monthly range of almost 5° F. (2.8° C.) less than Illinois or Pennsylvania. Some stations in southern Minnesota have less range than some in northern New York, in spite of the tempering influence of the Great Lakes. An illustration of the influence of vegetation on annual range is the fact that in Austria the average temperature in the forest is 2° F. (1° C.) lower in summer than outside of forests, while in winter the difference is negligible.[77]

24. *Annual or seasonal range increases with altitude up to the snow-line,* because at high altitudes heating of slopes inclined toward the sun is less interfered with by dense atmosphere, dust and mosture, than at lower altitudes, while cooling at night and in the winter is facilitated by the normally strong winds and by the reduced atmospheric interference with the escape of heat. Lofty plateaus have a greater range than lowlands in similar latitudes. For example, stations with an elevation of 5,000 feet (1500 m.) in eastern Oregon have a seasonal range of about 10° F. (5.5° C.) above that in eastern Washington at

[75] Hann, loc. cit., p. 142.

[76] Charts of Normal Temperatures and Extreme Temperatures for the United States, *U. S. Weather Bureau,* 1912.

[77] Hann, loc. cit., p. 31.

an elevation of less than 1,000 feet (300 m.) but otherwise similar.[78] Above the snowline, however, the seasonal range is not so great because summer temperatures are prevented from rising nearly so high as they do below the snowline.

25. *Seasonal range in temperature is affected by topography.*—Slopes inclined sharply toward the midday sun are warmer in summer than those not so inclined, while in winter they may be equally cold, and thus have the greater range. Favorably situated valleys are usually warmer than nearly level stretches (although they may sometimes be notably colder at night—see No. 18, above). Such valleys are normally warmer because: (1) Foehn breezes or winds often prevail; (2) the more effective heating of those portions which receive vertical insolation may more than compensate for the less effective heating of slopes not so favorably situated for heating as are level tracts. (3) Radiation from the sides of warm valleys interferes with loss of heat by radiation from the valley bottom, or in case of a narrow valley, from the other side,[79] probably because of the larger radiating surface in proportion to the volume of air within the valley receiving the radiated heat. Some favorably located areas have their temperatures notably affected by reflection from water bodies, snow, or light soils. The maxima are often several degrees higher than those at nearby points.[80] The minima are usually as low, because diurnal and extreme minima normally occur at night. Furthermore, by day the sun shines at a lower angle in winter and the reflection thus affects a different area.

Variability from Year to Year. 26. *Variability or irregularity in temperature conditions from year to year and for corresponding months tends to increase with latitude nearly to the region of persistent snow, with aridity, with storminess, and with decrease in the influence of the ocean.*—Equatorial days and seasons resemble one another strikingly in so far as temperature is concerned, while in mid-latitudes, no year or season is "normal." Temperatures are distinctly more uniform in humid areas than in arid regions otherwise similar. Variability increases with latitude for a number of reasons: (1) Slight fluctuations in the effectiveness of insolation and radiation are more appreciable where little insolation is received than where much is received. Differences in cloudiness and precipitation produce fluctuations of this sort in high latitudes. (2) Changes from year to year in direction and velocity of the wind produce greater changes in temperature in

78 Charts of Normal Temperatures and Extreme Temperatures for the United States, *U. S. Weather Bureau*, 1912.

79 Davis, loc. cit., pp. 31, 157.

80 Hann, loc. cit., p. 40.

high than in low latitudes, where nearly all winds are warm. Differences in storm paths and storm intensity produce many such changes in the average wind direction for the year. (3). In so far as storminess increases with latitude it helps to explain this law. The greater variability of weather in winter than in summer is largely due to greater storminess in winter. The stabilizing influence of snow and ice makes polar conditions somewhat more uniform in some respects than those in subpolar regions. Variability increases with distance from the ocean because of the lessening influence of that great stabilizer of temperature conditions. Variability increases with aridity because irregularity in the amount of clouds and surface water increases in that direction. An exception to this latter rule occurs in extremely arid regions on the lee side of mountains where conditions are fairly uniform. Illustrations of this general law are Hann's statements that a 40-year record would be required in Central Europe to obtain as accurate an average annual temperature as a two-year record from Java would give. In Siberia records for more than 100 years would need to be averaged to obtain a monthly average as accurate as a five-year record would give in Java. Eight hundred Siberian winters would give an average no more nearly correct than would 100 summers.[81]

[81] Hann, loc. cit., pp. 9, 10.

CHAPTER III

LAWS CONCERNING WINDS

KINDS OF WINDS.

27. *There are three great kinds of winds: (1) planetary, (2) continental, and (3) cyclonic.*—The first are due chiefly to latitudinal differences in insolation; the second to differences in heating and cooling of land and water. Cyclonic winds are due in part to other causes, not well understood. Minor winds include mountain and valley breezes and winds associated with tides, land slides, earthquakes and explosions.[82]

DIRECTION OF WINDS.—*Effects of Temperature Differences.*

28. *Surface winds commonly blow from colder areas to neighboring warmer areas because warm areas usually have lower air pressure than nearby cooler areas, and winds blow from places of higher air pressure to places of lower air pressure, though at a small angle to the isobars where friction is slight.*—Great insolation along the heat equator gives rise to persistent winds (the planetary circulation). Other more local winds, due indirectly to differences in air temperatures, are land and sea breezes,[83] monsoons, and valley and mountain breezes. There are two exceptions to this general rule. If an area is excessively heated for a very short time, only the flow of air away from the heated area has time to take place.* Furthermore, with every mid-latitude cyclonic storm, part of the wind comes from warmer areas.

29. *A great system of winds (the planetary circulation) results from the combined influence of intense equatorial heating and of the earth's rapid rotation.*—Intense insolation produces low pressure along the thermal equator.[84] The deflective effects of the rotation of the earth produces low pressures in high latitudes (lowest about 60° instead of near the poles largely because of the chilling influence of the snow caps).[85] Between the equatorial and subpolar belts of lower pressure, a belt of relatively high pressure occurs near the margin of the tropics

---

82 Shaw, W. N.: Principia Atmospherica, Laws of Atmospheric Motion, *Mo. Weather Rev.*, Vol. 42, pp. 196-209, 1914.

83 Ward, R. De C., Land and Sea Breezes, *Mo. Weather Rev.*, Vol. 42, pp. 274-277, 1914.

* See Law 32, beyond.

84 Blair, W. R., The Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, pp. 186-196, 1916.

85 Shaw, W. N., loc. cit. pp. 208, 209.

(averaging about 35° N. and 30° S., but shifting with the seasons). From the barometrically higher parts of this high pressure belt, winds blow toward the equator (the Trades) and toward the poles (the Westerlies in part). These higher centers of the Belt of Highs lie over the ocean because of the comparatively low temperature there, caused in part by the upwelling of cold waters.[86] The Horse Latitude Highs are maintained by the Anti-trades supplemented by the centrifugal force between the eastward blowing Westerlies and westward blowing Trades.†

† The importance of the planetary circulation is so great that it seems worth while to supplement the foregoing simple statement with a fuller one which presents the causes in another way. This statement is based on one kindly contributed by C. F. Brooks.

The great heating of the air in the tropics results in a greater expansion there than in any other belt. The consequent raising of the layers of air especially over the heat equator causes a poleward overflow. Before reaching many degrees of latitude from the equator the deflective effects of the earth's rotation begins to affect this overflow until by the time latitude 30 or 35 is reached the poleward flow is largely arrested, by being converted into an eastward movement. The flow of air from the equatorial regions and its concentration at latitudes 30-35 N. and S. makes a low pressure belt in low latitudes and high pressure belts on either side, at the earth's surface. The low pressure belt is developed most strongly over the lands, where the expansion due to heating is greatest, and the high pressure belts are best developed over the oceans where the coolness allows a greater compactness of air than is possible over the hotter lands. In high latitudes the cooling over the polar ice-caps contracts the air and allows an inflow from the surrounding regions. In high latitudes, however, the defective effects of the earth's rotation are so great that such inflow can come from but limited distances. The result is the development, at the surface, of high pressures over the polar ice caps, and of broken rings of low pressure at latitudes 60 to 65. Here as in low latitudes the lowest pressures develop over the warmest portion for the latitude (here the ocean in winter, the land in summer), and the highest pressures over the coldest portion, the reverse. The surface winds induced by these belts of pressure tend to modify them by centrifugal action, which in the case of the westerly winds of middle latitudes intensifies the subpolar low pressure belts and the horse latitude high pressure belts, particularly over the oceans, where the slight friction favors strong winds. (The deflective effect of the earth's rotation, per se, cannot modify the wind velocities, and therefore cannot modify gradients. It does, however, prevent the winds from obliterating gradients rapidly by direct flow. Centrifugal action, however, on curved wind paths can increase the gradient of pressure, and thus increase the wind.) Middle and high latitude lands in winter and intermediate and low latitude lands in summer, acting by themselves in cooling or heating the air, produce on a smaller scale the changes and circulation characteristic of the planet as a whole, and being superimposed on these worldwide changes, greatly complicate the distribution of pressure and the resulting winds.

86 McEwen, G. F., Peculiarities of the Californian Climate, *Mo. Weather Rev.*, Vol. 42, pp. 14-23, 1914. Humphreys, however, believes that friction is the chief factor.

30. *Appreciable local differences in the heating or cooling of the earth's surface often deflect general surface winds.* Cool areas such as snow-fields and lakes in summer often divert surface winds because such places commonly have a comparatively high air pressure, and hence tend to have outblowing winds.[87] Winds also sometimes change their direction during the day, blowing toward the area of greatest insolation.[88] Likewise lake and sea breezes often shift conspicuously, chiefly because of the deflective effects of the earth's rotation, but partly because of the hourly changes in the area of greatest heating.[89]

31. *Winds are deflected by the rotation of the earth, to the right in the northern hemisphere and to the left in the southern.* (Ferrel's Law.)[90] The deflective effect of the earth's rotation increases as the sine of the latitude from nil at the equator to a strong effect near the poles.[91] As a result of this deflective effect the Trades are easterly instead of north or south winds, and the planetary winds of mid-latitudes are westerly, instead of north or south winds. Land and sea breezes "veer" notably in the northern hemisphere and "back" in the southern chiefly because of this deflective effect. The direction of the winds about Lows and Highs and in tropical cyclones also complies with Ferrel's Law.

Effects of Topography.

32. *The prevailing wind direction is peculiar at many points, especially in rugged regions, because surface wind directions are influenced by topographic features.*—Mountain ranges and lesser elevations frequently divert winds, for winds tend to descend valleys and other slopes,[92] because gravity interferes with ascent but facilitates descent. For the same reason wherever slopes are ascended by general winds, valleys are often followed conspicuously.[93]

---

87 Henry, A. J., The Winds of the Lake Region, *Mo. Weather Rev.*, Vol. 35, pp. 516-520, 1907, and Davis, T. H., Direction of Local Winds as Affected by Contiguous Areas of Land and Water, Ibid, Vol. 34, pp. 410-413, 1906.

88 Pernter, J. M., Causes of Diurnal Changes in Wind, *Mo. Weather Rev.*, Vol. 42, p. 661, 1914.

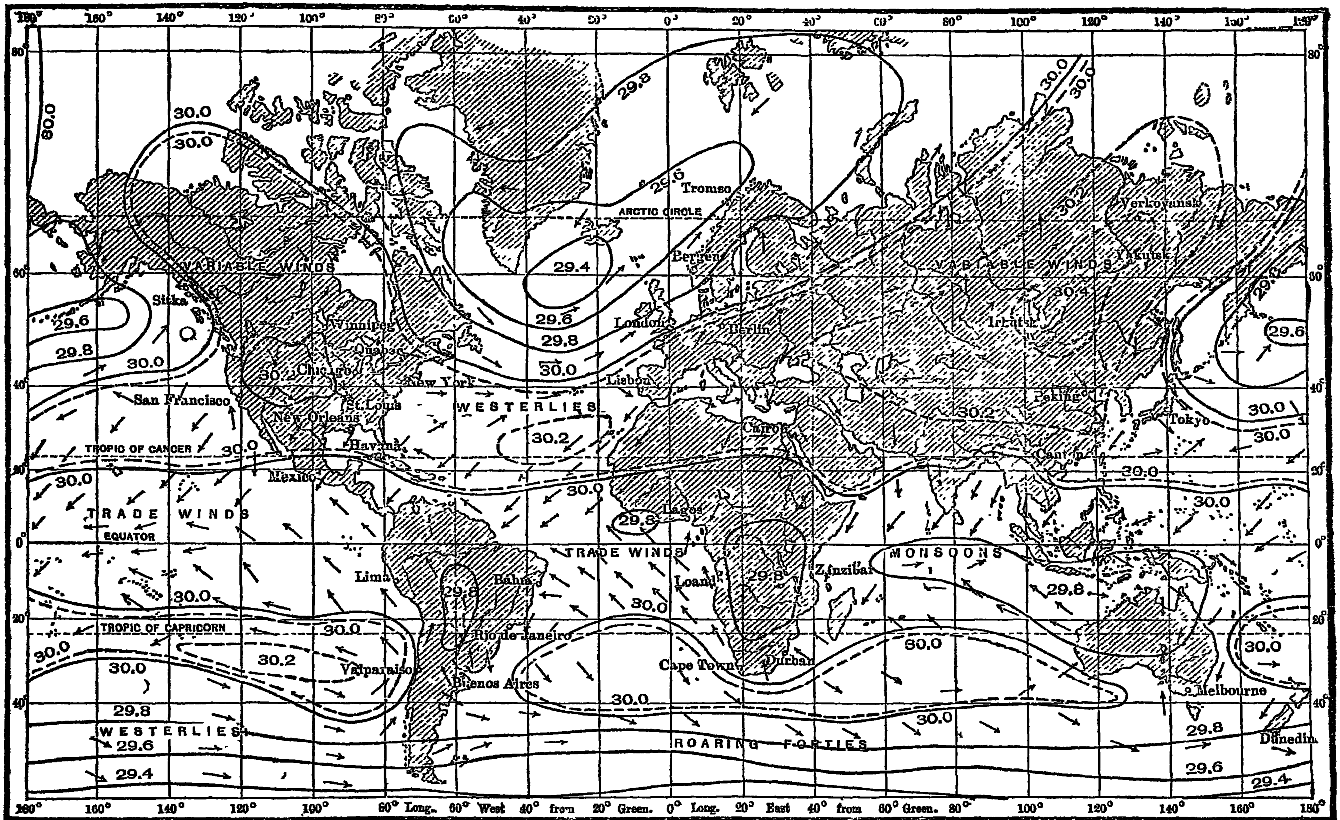
89 Humphreys, W. J., in National Research Council, Introductory Meteorology, p. 106, 1918.

90 Ferrel, Wm., A Popular Treatise on the Winds, 1890.

91 For table showing radius of curvature of deflection for different latitudes see Davis, W. M., Elementary Meteorology, p. 104, or Milham, W. I., Meteorology, p. 161.

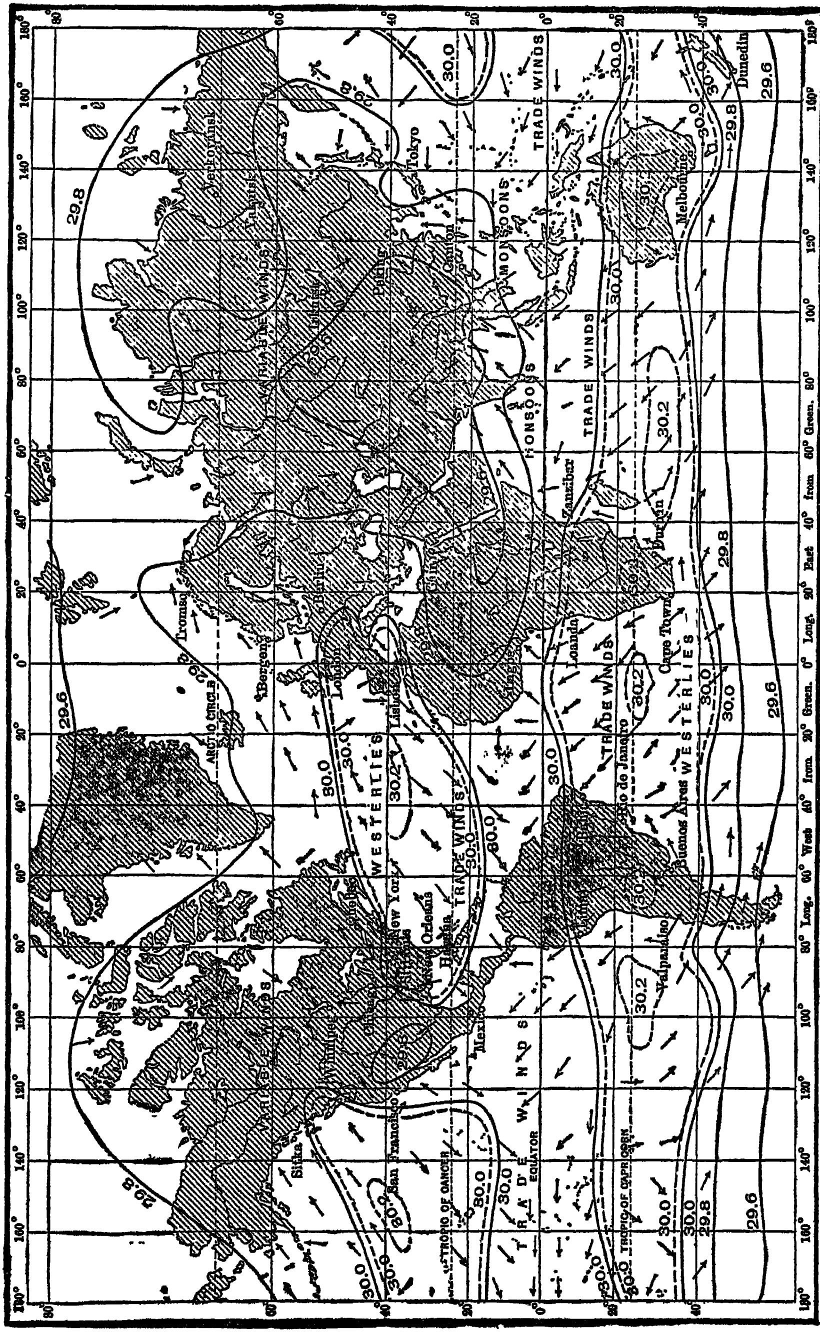
92 Day, P. C., Winds of the U. S., *Yearbook of the Dep't of Agriculture for* 1911, p. 340, and Henry, A. J., Climatology of the U. S., *Bull. Q., U. S. Weather Bureau*, pp. 67-75, 1906.

93 Davis, W. M., Elementary Meteorology, p. 98, Figs. 29, 30; 1894.



——— indicates pressures below 30 inches

FIG. 3.—Average Pressure and Winds in January. (From Huntington and Cushings' Principles of Human Geography.)



—— indicates pressures below 30 inches

FIG. 4.—Average Pressures and Winds in July. (From Huntington and Cushings' Principles of Human Geography.)

Seasonal Changes in Direction.

33. *A seasonal change in average wind direction is common.* Changes are produced in three ways: (1) By the seasonal migration of the wind belts, (2) by the development of typical monsoons, (3) by the frequent deflection of the planetary winds caused by high and low pressures produced by unequal heating and cooling of continent and ocean. Many subtropical areas are within the Trade Wind belt in summer and within the Westerly wind belt in winter. Other subtropical or warm temperate areas have land monsoons in winter and ocean monsoons in summer. Farther north, in the northern hemisphere, there is likewise a seasonal change in average wind direction due to changes in average barometric pressure. Continents commonly have high average pressures in winter and low average pressures in summer. Thus there is a strong tendency for barometric minima to develop over oceans in winter. Hence southerly or westerly winds predominate in winter on western coasts, and northwesterly winds on eastern coasts. For example, southwest winds predominate in winter in western Europe and in western North America, north of California, while northwest winds prevail in eastern North America and in eastern Asia. Conversely, in summer low pressure over the drier parts of the continent commonly give rise to southerly winds on the eastern side of the continents, and northwesterly winds on the western side. For example, the average wind direction in summer for the eastern half of the United States, is from the southwest or south and that of eastern Asia from the southeast, while at the same time western Europe and western United States are having northwesterly winds.[94]

Changes with Altitude.

34. *Wind direction aloft is different from that nearer the surface usually being more to the right of the surface direction* (in the northern hemisphere). At higher and higher elevations up to a height of about 2,000 feet (610 m.) the wind makes a progressively greater angle with the line representing the steepest gradient, that is, they blow at a smaller angle with the isobars. This is because with decrease in fric-

[94] Hann, loc. cit., pp. 172-178, gives several tables showing average monthly wind directions for stations in Europe, Asia, and North America. He also states that continents resemble cyclones in summer and anticyclones in winter. Köppen's charts for normal wind directions on the ocean for July-August and Jan.-Feb. are reproduced in Moore's Descriptive Meteorology and in Humphreys, Physics of the Air. See also Ward R. De C., The Prevailing Winds of the U. S., *Annals Assoc. Am., Geographers*, Vol. 6, 1916, pp. 99-116 (abstracted in *Mo. Weather Rev.*, Vol. 47, pp. 575-576, 1919).

tion the flow of air with a given gradient is more rapid, and therefore the deflection is greater, thus bringing the wind direction more nearly parallel to the isobars. At even higher elevations, where friction is only slightly less, wind direction continues to change, becoming progressively more nearly parallel with the isobars, which at high altitudes seldom depart more than 30° from an east-west direction. This change is because of the increase in centrifugal force which accompanies increased velocity, and occurs in spite of the fact that the decrease in the earth's rotational deflective effects, which accompanies the increase in wind velocity with altitude, tends to make the wind direction less nearly parallel to the isobars. The weakening of the pull of gravity permits the centrifugal tendency to overcome the tendency to turn to the right (northern hemisphere).[95]

Diurnal Changes.

35. *Surface winds at low altitudes often "veer" during the day and "back" at night. At higher altitudes the diurnal shifting is commonly in the opposite direction.*—A diurnal change of 12° in wind direction is common. This shifting is due largely to convectional interchange between the wind at the earth surface and that at a moderate elevation. During the day, convection causes masses of air from above to descend to the surface. These layers tend to retain their somewhat different direction of general movement, mentioned in the preceding law. Hence at low altitudes there is a tendency to shift to the right in the northern hemisphere ("veer"). At night, when convection is much less intense or is lacking, the surface friction forces the wind to blow at a larger angle with the isobars and as this adjustment takes place the wind shifts counter-clockwise ("backs"). At higher altitudes, a few hundred feet above the surface in winter and 2,000 or 3,000 feet (610 or 914 meters) in summer,[96] the wind direction changes in the opposite way to that at low altitudes because at night less friction is induced by upward convection than by day, since there is comparatively little convection at night. Hence the air at higher levels can flow at a smaller angle with the isobars by night than it can by day. Along coasts there is often a marked progressive shifting in

---

[95] See Shaw and others, Meteorol. Glossary, loc. cit., pp. 134-137, 171-173 and also Humphreys: Wind Velocity and Elevation, *Mo. Weather Rev.*, Vol. 44, pp. 14-17, 1916.

[96] Hellmann, *Mo. Weather Rev.*, Vol. 45, p. 454, 1917; Dunoyer and Reboul, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918. Taylor, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

the land and sea breeze. Sometimes it reaches nearly 90°.[97] This shifting is produced chiefly by the deflective effects of the earth's rotation on the air which comes from a progressively greater distance from the shore line until the breezes finally die down.

WIND VELOCITY.—*Variations with Latitude and Altitude.*

36. *Average wind velocities increase with latitude to about 45° or 55° N. and S., except for the horse-latitude calm belt.*—This is because winds strengthen, on the average, with the steepening of the barometric gradient and the greatest average interzonal gradients are about 45°-55° N. and S. The correspondence between gradient and velocity is not constant, however, because of various influences, some of which are mentioned below. Normally in mid-latitudes, a ten-mile-an-hour (4.5 meter per sec.) surface wind is to be expected when isobars representing a barometric difference in pressure of one-tenth inch (3.4 mb.) are 170 miles (270 km.) apart, a 25-mile (11.2 meter per sec.) wind when such isobars are 70 miles (110 km.) apart, and a fifty-mile wind (22 m. p. s.) when 35 miles (56 km.) apart.[98] Above the surface 1500 feet (460 meters) or so the wind is little affected by surface conditions and hence the relation between gradient and velocity is much closer, as is also the case at sea. Under such conditions the winds become almost gradient winds. The velocity of gradient winds is almost exactly doubled as the distance between isobars is halved. Where isobars of .3 inch (10 mb.) are about 900 miles (1450 km.) apart, the wind blows about 11 miles per hour (5 meters per sec.), and where about 100 miles (161 km.) apart, the velocity is about 100 miles per hour (45 m. per sec.). The gradient velocity increases, however, with latitude, about 20 per cent between latitudes 40 and 52, and decreases with increasing temperature, about 10 per cent between 32° F. and 104° F. (0° C. and 40° C.).[99] The increase in average velocity with latitude (to about 45 or 55 N. and S.) is also associated with the average increase in storminess to about those latitudes. Furthermore, wind velocities are on the average slight near the equator partly because the deflective effect of the earth's rotation is so small there that the air flows rapidly into an area of low pressure and fills it promptly and then dies away instead of circling round and round as it does in higher latitudes. The decrease in average velocity in polar regions is not due to the total lack of strong winds, for gales, usually of the drainage or the monsoon

[97] As at the Chicago Crib in July where the wind is normally from the east at 1 P. M. and shifts to nearly due south by 10 P. M., Davis, loc. cit., p. 135. See also Cox and Armington, The Weather and Climate of Chicago, p. 305, 1914.

[98] Walz, after G. Guilbert, in Weather Forecasting in the U. S., p. 140, 1916.

[99] Computed from Shaw, Meteorol. Glossary, pp. 172-173.

type but sometimes foehns, often occur locally in polar regions, especially near the edges of glaciers. However, calms are frequent, so the average wind velocity for polar regions is low.[100]

37. *Wind velocity normally increases with altitude, rapidly over an area of much surface friction and less rapidly over an area of little friction,* such as the sea. There is commonly a rapid increase in velocity from the surface up to the height of the taller local objects interfering with air movement (trees, hills, etc.).[101] Above that level the increase is at a much lower rate; between 2000 feet and 3300 feet (600 and 1000 meters) there may be no considerable increase. Above an elevation of a mile or so (2 km.), there is an average increase of between one and two miles per hour (.5-.9 m. per sec.) for each rise of 1000 feet (300 m.), up to an elevation of three to five miles (5-8 km.), an increase in velocity sufficient to compensate for the decrease in density, so that each 1000-foot layer carries the same mass of air past a given line per hour. (Clayton's Law, often known as Egnell's Law). The velocity increases to an altitude of about five miles (8 km.), where it often reaches more than 100 miles per hour (45 m. per sec.).[102] Beyond the five-mile level (8 km.), Clayton's Law does not hold, and the velocity falls.

38. *Surface winds average stronger over smooth surfaces than over rough, in similar latitudes* because surface friction reduces the velocity which can occur with a given barometric gradient. Hence winds are normally stronger on water than on land, stronger on plains than over

---

100 Ward, Climate, p. 174, Wilkes Land in the Antarctic is an exception (Ibid, p. 176). There cyclonic storms are severe. Also see Simpson, G. E., The Meteorology of the Antarctic, *Mo. Weather Rev.*, Vol. 49, pp. 305-306, 1921.

101 The greater velocity commonly recorded at U. S. Weather Bureau Stations in large cities than in small places is because the city aneometers are located on relatively tall buildings. Near the ground the average velocity of the wind is proportional to the 4th or 5th roots of the heights, according to Hellmann, *Mo. Weather Rev.*, Vol. 47, p. 574, 1919. In other words, according to Chapman, (Ibid, p. 572) it is a lineal function of the logarithm of the height.

102 Humphreys, W. J., Wind Velocity and Elevation, *Mo. Weather Rev.*, Vol. 44, pp. 14-17. However, Maurain, C., Ibid, Vol. 47, p. 809, 1919 gives much lower velocities. He reports the maximum velocity experienced by many balloons to be 15.6 meters per sec., (35 miles per hour) and at 11,000 meters 67 miles. Above that height a decrease occurs to about 18 miles per hour (8m. per sec.) at 19,000 m. (12 miles). Velocities in excess of 100 miles an hour (45 m. per sec.) are rare, according to these French balloon data, but one balloon travelled at the rate of 123 miles an hour (55 m. per sec.). A balloon over England travelled 180 miles per hour (80 m. per sec.) at 26,000 feet (7925 m.) on Jan. 19, 1920 Ibid, Vol. 48, p. 41, 1920.

rugged areas, and stronger over grass-covered or barren areas than over forests. A mantle of snow or ice also tends to increase wind velocity by lessening friction. The average velocity of surface winds on the sea is estimated to be twice that of winds on land.[103] Hence along the coasts the average velocity is notably higher than it is a short distance inland. For example, the wind velocity is often only half as great on the east coast as on the west coast of the British Isles, with a west wind and equal barometric gradients.[104]

Effects of Insolation and Humidity.

39. *Winds are often especially strong at the surface by day in places of great insolation.*—This is because convection is strong and hence rapidly moving air from above replaces the warmed air as it rises, in fact causes it to rise. Where much air is quickly warmed, large amounts of rapidly moving air usually descend. Even if they do not descend to the surface, they increase the friction between the surface layers and the faster moving upper layers, which tend to drag the lower air along.[105] The extent of this knitting by day has been discovered by aviators who find that currents induced by local convection are often noticeable at heights of 2000 feet (600 m.) and sometimes 10,000 feet (3,050 m.) or more above the surface on clear days.[106] Hence where a heavy mantle of clouds retards insolation, as is often the case in humid climates, the surface wind velocity on a hot day is often much less than on a clear day with its usually greater convection. Often narrow, deep valleys may be nearly calm in spite of intense insolation because the wind, if at right angles to the valleys, may not descend to the floor of the valley before it commences to ascend the other side. An example is Death Valley, California.

40. *Winds associated with rapid convection are strongest in the season and at the time of day when convection is greatest,* which usually is shortly after the time of greatest insolation. Although insolation is greatest and the vertical temperature gradient is steeper just before noon than at noon, convection commonly intensifies for some time after noon, and after the summer solstice. Insolation averages greater just before noon than at noon because of less average cloudiness then; convection is greater shortly after noon and after the summer solstice than when the sun is most nearly vertical because of the lag in surface tem-

103 Meteorol. Glossary, loc. cit., p. 122.

104 Ibid., p. 123.

105 Pernter, loc. cit., p. 662.

106 Brooks, C. F., Effects of Winds and Other Weather Conditions on the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

peratures (Law 14). Thunder-storms with their associated squall winds occur on the land chiefly in early summer in mid-latitudes and at corresponding seasons in low latitudes. Dust whirl-winds also are most frequent then and near noon. Tornadoes are most numerous in May and June in the northern hemisphere. On the other hand, upon the ocean, in high latitudes especially, the vertical temperature gradient is greatest in winter, because then the surface air is kept relatively warm by the water. Hence high-latitude ocean thunder-storms are most frequent in winter.[107]

41. *With a given barometric gradient, wind velocity tends to increase slightly with absolute humidity*, because water vapor is less viscous and lighter than dry air. (Molecular weight of air is about 29, while that of water is only 18.) The wider average spacing of isobars in the warmer latitudes and in summer is in part an indirect result of this greater amount of water vapor.[108]

Effects of Direction.

42. *Non-planetary winds blowing with the planetary circulation are stronger than similar winds blowing in other directions* because the planetary circulation augments their velocity if they are blowing with it, or checks their velocity if they are blowing against it. This law largely accounts for the "dangerous side" (poleward, right) of tropical cyclones; for the greater velocities on the equator-ward (right) side of extra-tropical cyclones and on the poleward side of anti-cyclones; for the greater influence of sea and lake breezes on the eastern shores of water bodies in the belt of Westerlies and on the western shores in the Trades; and also for stronger monsoons on one side of some land areas than on other sides quite similar in other respects.

43. *Exceptionally cold winds are often more powerful than relatively warm winds* because such cold winds commonly have a greater velocity and density. The greater velocity is partly caused by the recent descent from somewhat higher altitudes, of which their greater than average downward component is evidence.[109] It is also associated with the steep pressure gradient caused by the exceptionally cold and therefore dense air of the northwesterly winds in contrast to the warm southerly winds usually occurring immediately to the east (in the Northern Hemisphere). Their greater density is related to their low temperature. Their density enables them to push harder than less dense winds.

107 Humphreys, Physics of the Air, p. 324.

108 Davis, loc. cit., p. 153.

109 See H. H. Kimball, Northwest and Southwest Winds Compared, *Mo. Weather Rev.*, Vol. 48, p. 147, 1920.

In the northern hemisphere, northwest winds average the coldest. They also average the strongest, for the above mentioned reasons and because they are aided more by the prevailing westerlies than are the winds from most directions.

Seasonal and Diurnal Variation.

44. *Wind velocities average greater in winter than in summer in mid-latitudes.*—The lessened average barometric gradient of summer which largely produces the lesser summer velocity is related to: (1) lessened storminess in summer (most widespread high winds in mid-latitudes are associated with intense Lows); (2) the greater absolute humidity of summer permits a freer wind movement and thus tends to facilitate an equalization of barometric differences; (3) the fact that the isotherms are farther apart in summer than in winter results in the isobars usually being far apart also; (4) the barometric gradients are also affected by the temperature gradients, which often are steeper in winter than during most of the summer. Another factor tending to reduce the velocity of the wind in summer is the greater friction resulting from vegetation and from local contrasts in surface heating with their resulting convectional disturbances. Gales are commonly much more frequent in winter than in summer. For example, on the British coasts, gales are more than six times as likely to occur on any day in the six months October to March, as on a day in the three months June to August.[110]

45. *The surface winds on the land commonly increase in velocity during the day until early in the afternoon, except at high altitudes on mountain peaks.* The increase in velocity accompanies the increase in convection.[111] It is due to an interchange of surface air and the faster moving higher air. The diurnal increase is greatest when the sky is clear. On cloudy days the maximum surface wind velocity is, on the average, only about half what it is when the sky is clear,[112] because on cloudy days convection is less than on clear days. At many

[110] Meteorol. Glossary, p. 127. In some other areas, gales are most numerous in spring. For example, in South Dakota, though there are fewer gales in Dec. and Jan. than in summer, there are more than twice as many in April and May as in July and August. (Visher, S. S., Climate of S. Dak. p. 51, *Bull.* 8, *S. Dak. Geol. Surv.* 1918). In hurricane regions, on the other hand, gales usually are most frequent in autumn. (Visher, S. S., Tropical Cyclones of Australia, and the South Pacific and Indian Oceans and in the North Pacific, *Mo. Weather Rev.*, Vol. 50, pp. 288-297, 583-589, 1922).

[111] Pernter, loc. cit., Taylor: Phenomena Connected with Turbulence in the Lower Atmosphere, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

[112] Russell, T., Meteorology, p, 106, 1895.

places the average wind velocity is twice as great in the mid-afternoon as it is in the early morning. The diurnal variation in wind velocity almost disappears over the ocean with its nearly constant temperatures, and is less on the land in winter than in summer, and less on cloudy than on clear days, and less in the cooler regions than in warmer, because of the greater convection in summer and on clear days and in low latitudes. At high altitudes some distance above the surface, on the other hand, winds are stronger by night than by day chiefly because fewer convection currents reach a high level at night and hence there is less interference at night with the regular winds.[113] As an example: The average velocity on Pike's Peak is greatest from 2-4 A. M. (23.2 mi. per hour; 10 m. per sec.), and is least just before noon (17.5 mi. per hour; 8 m. per sec.). For the lowlands of the eastern United States, the hour of maximum wind velocity averages 2 P. M. and of minimum velocity 4 A. M., and the difference between minimum and maximum velocity averages two miles per hour (.9 m. per sec.) in winter and five miles per hour (2.2 m. per sec.) in summer.[114] At Kew, England, the diurnal variation averages six miles per hour (2.7 m. per sec.) in July and 2½ miles per hour (1.1 m. per sec.) in winter.[115]

STEADINESS OF WINDS.—*Variations in Latitude and Altitude.*

46. *In general there is a lessening of the persistence of winds with increased latitude accompanying the intensification of temperature variability,** because winds vary in persistence with changes in the permanence of the conditions or conditional complexes that produce them. The Trades are notably persistent because of the steady heating along the thermal equator. Monsoons are less reliable than the Trades because of the greater variation in the heating of continental areas near the borders of the tropics than along the thermal equator. Lake and sea breezes are strongest and most persistent when there

* See Law 25, above.

113 Hellmann, (*Mo. Weather Rev.*, Vol. 43, p. 58, 1915) ascribes this increase to the influence of the thermal wave caused by the earth's rotation. See Humphreys in Nat. Research Council, Introductory Meteorology, pp. 106-107, for additional, though probably very minor influences.

114 Waldo, F., Hourly Wind Velocities, *Am. Meteorol. Journ.*, Vol. 12, pp. 75-89, 145-151, 1895.

115 Shaw, Meteorol. Glossary, p. 86. The great diurnal increase in wind velocity at Hongkong is clearly shown on Plate 13 of Claxton, T. F., The Climate of Hongkong Royal Obs., 1916. The maximum normally is between 1 and 2 P. M. when the velocity averages one-third (4 miles per hour) more than at the minimum which occurs at 8 P. M. during 5 months, at 6 A. M. during 4 months and at 11, 2 and 7 A. M. on the others.

is greatest temperature contrast between land and water, as on clear days in hot seasons. Sea breezes are exceptionally prominent on west coasts in the Trade Wind belt for there not only is the land heated greatly by day but the surface ocean water is exceptionally cool by day as compared with the land, largely because of the upwelling of cold abysmal waters induced by the drift to the westward (contributory causes of the coolness are mentioned in Law 5). In general the sea breeze is better developed than the land breeze because the land is warmer than the sea throughout the year in low latitudes and in summer, the season of sea breezes, in higher latitudes.[116]

47. *Winds tend to increase in steadiness with altitude in the free air and on windward slopes, up to considerable heights,* because friction is less and disturbances are fewer.† The change with altitude is especially marked at night. In large parts of the world fitful breezes are the rule at night at the surface on lowlands, while at moderate elevations the wind is blowing steadily. (See next law.) The same condition often obtains on lowlands along coasts, before the sea breeze and land breeze make themselves felt at the surface.[117]

Variation with Diurnal Range of Temperature.

48. *Calm nights are common wherever the surface becomes much colder at night than it is by day,* and hence are characteristic of trade wind deserts and other dry parts of the land. Calm nights are abnormal on the ocean, except in the belts of calms, because of its nearly uniform surface temperatures.[118] Winds commonly die down at the surface of the land at nightfall because this surface is a comparatively good radiator and since it has a lower specific heat than air, it is soon cooler than the over-lying air. After the surface air is cooled by conduction and moderate radiation to the cooler earth, upward convection largely ceases because the colder, heavier air is at the bottom of the atmosphere. Friction tends greatly to retard the movement of this lower, heavier air. The wind tends to slip over the surface layers, and if it does slip over them a surface calm is induced. The completeness of the surface nocturnal calm depends on the amount of nocturnal convection, the

† See Laws 37, 38, 45, 48, 49, 50, for some effects of increased altitude on winds.

116 Hann, loc. cit., p. 160.

117 Davis, W. M., Elementary Meteorology, p. 136, 1894.

118 Humphreys points out (Physics of the Air) (p. 324) that because of the greater nocturnal cooling of the air than of the surface water, the temperature gradient over the ocean is most favorable to convection shortly before sunrise. Hence convection currents and thunderstorms are most numerous then. Surface wind velocity must also be greatest then, wherever the influence here discussed is dominant.

amount of friction, and the character of the wind. In dry regions, loss of heat by radiation is exceptionally rapid, and hence convection largely ceases soon after sunset. There is more friction over land than over water, and more in forested and rugged parts of the land than in grass covered or level areas. Winds with a notable downward component tend to prevent the development of a surface calm, whereas winds with an upward component favor its development. The Trades are of the latter sort,[119] as are the winds blowing into a Low from the equatorward side.[120] Those from a High, and on the poleward side of a Low have a distinct downward component. However, calms are frequent near the center of anticyclones,[121] where there is little or no barometric gradient to induce winds. In respect to latitude, the amount of nocturnal surface calm decreases, among places otherwise similar, with increase in latitude up to the poleward side of the great storm belts, roughly to latitude 55° N. and 45° S. This is because to the poleward of this belt, diurnal range is less, and cloudiness and equatorward blowing winds more frequent.

Sudden Changes (Gustiness and Puffiness).

49. *All winds vary in velocity and direction from minute to minute.* —Variation in direction, here called "gustiness" is considered in the following law. Variation in velocity, here called "puffiness," is caused largely by the convectional and frictional forces which produce variations in direction. One additional cause for continual change in velocity is the variation in pressure due to the passage of waves through the air, for example those oscillations associated with the constant shift, produced by the earth's rotation, in the longitude of greatest insolation. Frequent slight variations in air pressure are produced over the sea by the water waves and troughs. Tidal waves have some effect on air pressure even over the land. The fall of rain, the roll of thunder, and similar disturbances likewise produce slight variations in pressure. The elasticity of the air and its inertia are fundamentally important in connection with "puffiness." Variations in "puffiness," although always present, increase in amplitude, as expressed in miles per hour, with velocity of the surface wind. Often there is a variation of 10 or 20 miles an hour (4½ to 9 meters per sec.), in a few minutes during

119 Abbe, C.: The Mechanics of the Earth's Atmosphere, a Collection of Translations, *Smithsonian Miscellaneous Collections*, 843, 1893. (Paper by Prof. Oberbeck, p. 186.)

120 Blair, W. R., Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, p. 192, 1916.

121 Shaw, Meteorol. Glossary, p. 31.

a high wind. If expressed in per cents, the momentary increases are greatest when a breeze prevails, for then the velocity may double or triple within a few minutes. "Puffiness" is especially conspicuous over a storm-tossed sea, and it also appears to increase with latitude up to the storm belt. The winds about a well-marked Low are particularly "puffy."

50. *Momentary change of direction or gustiness increases on the average with increased surface friction, with approach to the desert, the equator and the bottom of the atmosphere, and in general with increase in convection and in local contrasts in heating.*—The decrease in gustiness with latitude is due to the fact that convection decreases on the average with increase in latitude. The increase with aridity accompanies a general intensification of convection. Objects which produce friction cause some air to rise and later to fall, in order to pass over the object or over the air which has been piled up as a result of friction.[122] Gustiness decreases with height above the surface because most vertical currents induced by local convection or friction only affect the lower few hundred feet of air, and relatively few affect as much as the lower 2500 feet (760 m.).[123] (Vertical local convectional currents are felt twice as high in summer as in winter in some regions).[124] Local contrast in heating is produced by contrasting types of soil or vegetation, the presence of bare areas, of streams, of small lakes or marshes, and of significant differences in slope or relief. Such differences often produce gustiness because air often rises above the warmer areas and descends over the cooler. Cumulus clouds are striking evidences of such unequal heating.[125] Wherever and whenever local convection is least, gustiness due to local convection is least. Therefore this type of "bumpiness" is less in the relatively calm, cloudless weather of an on-coming High than in an on-coming Low with its patches of clouds, and its stronger winds.[126] Because of the importance of local convec-

[122] Convection is also caused by overriding of one layer of air by another. Easterly winds especially are lighter than westerly winds and are often overridden. This would tend to produce convection. (Shaw, W. N., *Mo. Weather Rev.*, Vol. 42, p. 198, 1914; and see also Brooks, Kimball and Humphreys, Ibid., Vol. 48, pp. 100, 101, 147; 1920.

[123] "Gustiness falls off rapidly in the first 500 feet of ascent, and thereafter it is irregular." Dines, W. H., Meteorol. Glossary, p. 142.

[124] Brooks, C. F., Winds and the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

[125] Another excellent indicator of convection and of turbulence due to friction is smoke from a smokestack. See Etkes and Brooks, *Mo. Weather Rev.*, Vol. 46, pp. 459-460, 1918.

[126] Shaw, Meteorol. Glossary, pp. 21-23.

tion in producing gustiness, the latter is far less noticeable over the sea than over land,[127] at night than by day, in winter than in summer, and less intense over a fog or low cloud than at corresponding altitudes where such barriers to insolation and convection are not present. The lessened gustiness over the sea and on the land in winter is due to the comparatively slight friction. Gustiness increases with aridity only where surface conditions are similar, which seldom is the condition. In arid regions there usually are few trees, fields, roads and buildings. Hence there is less contrast and less friction. Thus, instead of increasing with aridity, gustiness often decreases. Gustiness was not considered as an aspect of climate until surveyors, astronomers and aviators revealed considerable geographic permanence of differences in "visibility" and in "bumpiness." Surveyors find that the visibility of distant objects usually decreases from morning to mid-afternoon and then increases; that the "seeing" is better on a cloudy day than on a clear or partly clear day; and that on clear days "seeing" is better in cool climates than in warm. These variations in visibility are apparently related to local convection, the great cause of gustiness. Astronomers find the "seeing" poorest on windy nights and best on calm nights. The fact that nocturnal "seeing" is especially favorable in deserts is probably related not so much to less humidity, as to the lack of nocturnal convection. The excellent vision at night at Mandeville, Jamaica, where the annual rainfall normally is 87 inches (2210 mm.), but where, for special reasons, the nocturnal convection is slight, supports this view.[128]

---

127 Taylor, loc. cit.

128 Pickering, W. H., *Mo. Weather Rev.*, Vol. 47, p. 574, 1919; and Vol. 48, p. 511, 1920.

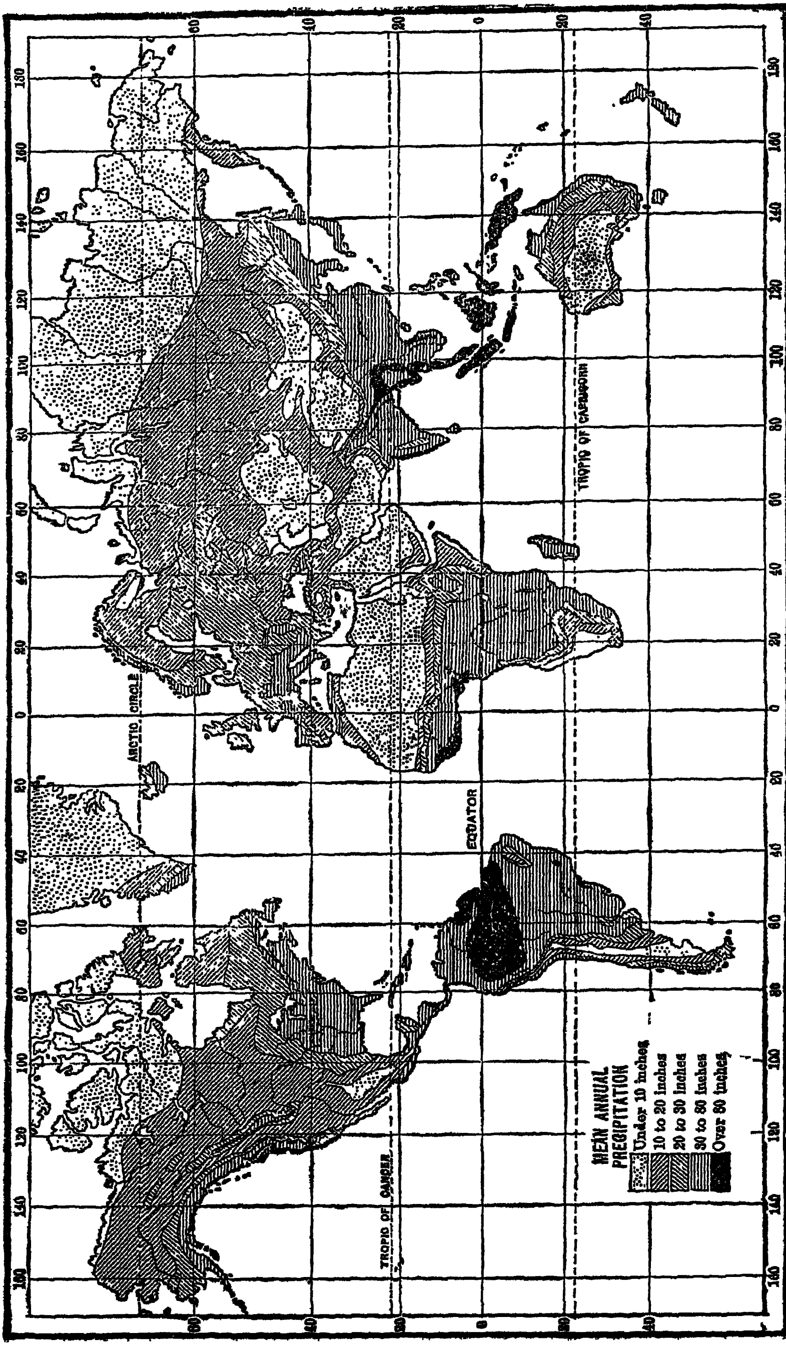


FIG. 5.—Mean Annual Rainfall. (From Huntington and Williams' Business Geography.)

CHAPTER IV

LAWS CONCERNING ATMOSPHERIC MOISTURE

SOURCES OF MOISTURE.

51. *Atmospheric moisture is derived by evaporation from all moist surfaces, chief of which is the ocean,* as the ocean covers three-fourths of the globe and more than four-fifths of its warmer half. Evaporation from soil, vegetation, animals and water on the land is the immediate source of much vapor. It should be borne in mind however, that a lake, even a large lake, is no more an ultimate source of water vapor than is ground moistened by a shower; both are temporary resting places of water en route to the sea. Nevertheless, much rainfall on the land is derived from moisture recently evaporated from such resting places. The small amount of evaporation taking place at low temperatures during the winter, when there is often much snow or other moisture on the ground, is one cause for the lesser precipitation in the cold season than in the warm in many inland places. When spring comes with its higher temperatures, accumulated moisture of the winter is soon largely evaporated and often partly reprecipitated, giving rise to spring showers. Some of it remains in the air, however, until the autumnal cooling.

RATE OF EVAPORATION.

52. *The potential rate of evaporation at any point normally increases with the temperature and hence usually is greatest at the warmest time of the day and year.* At night condensation often takes place instead of evaporation. This variation occurs because the capacity of space to hold moisture increases sharply with the temperature. Twenty times as much moisture can be contained in a given space at 100° F. (38° C.) as at 15° F. (—9° C.).[129] The capacity is approximately doubled or halved with each change of 18° F. (10° C.). The local rate of evaporation is affected also by the wind velocity and, as there commonly is also a diurnal intensification of wind velocity corresponding with the diurnal rise of temperature,[130] the wind regime

[129] Tables of capacity in vapor pressure and in quantity of water vapor per cu. ft. at different temperatures are given by Milham, Meteorology, p. 195, and in texts on physics. A full table showing vapor pressure for relative humidities at different temperatures is given in *Smithsonian Meteorol. Tables,* pp. 183-185 and pp. 192-193, 1918.

[130] The close similarity of the diurnal curves of temperature and wind velocity is strikingly illustrated at Chicago. See Cox and Armington, Weather and Climate of Chicago, p. 314, 1914.

helps explain the diurnal change in evaporation. The wind is significant as a factor affecting the rate of evaporation because it carries away the saturated or partly saturated air. When other conditions are uniform, the rate of evaporation is roughly proportional to the square root of the wind velocity.[131] The influence of the higher average velocity of wind in winter, however, is usually counteracted by the lower temperatures.

The rate of evaporation depends also upon the humidity of the air in contact with a moist surface and the temperature of that surface. If the surrounding air contains much less moisture than it can hold at its temperature, evaporation will be relatively rapid; if it is nearly saturated, evaporation will be relatively slow. If the moist surface is warm, evaporation is more rapid than if it is cold. The more rapid evaporation on clear days than on cloudy days in mid-latitudes is due chiefly to the fact that air is commonly drier on clear days than on cloudy days, even though it is sometimes cooler. The greater insolation in clear weather is significant because it tends to maintain the surface temperature, and thus allows evaporation to continue at a faster rate than the dry air alone would permit. Clear days in mid-latitudes usually are associated with anticyclones in which the air is descending and being warmed dynamically.

53. *The rate of evaporation diminishes on the average at progressively higher latitudes and altitudes and also with approach to marine conditions.* The change with latitude is associated with a like change in temperature. The Trades are drying winds except where ascending because they blow into progressively warmer latitudes. Decrease in the rate of evaporation with approach to marine conditions is influenced by increased relative humidity, and in all but cold places, also by lessened average temperatures. Within the tropics there is an average annual evaporaton of 30 inches (760 mm.) and in the polar regions less than 10 inches (250 mm.). In general, evaporation exceeds precipitation in the lower latitudes while precipitation exceeds evaporation in the higher latitudes.

The general decrease in evaporation with increase in altitude is the result of lessened temperatures and this decrease takes place in spite of the influences of decreased air pressure, lower absolute humidity, and stronger winds, all of which tend to increase the rate of evaporation. Hence, whenever temperatures at high altitudes are equal to those at low altitudes the rate of evaporation tends to increase with altitude. Furthermore the low absolute humidity characteristic of high alti-

131 Hann, Handbook of Climatology, Vol. 1, translated by Ward, p. 44, 1903.

tudes strikingly affects the rate of evaporation whenever temperatures are suddenly raised. When cold air, saturated perhaps but containing only a little moisture, is warmed, it becomes relatively dry, and thus evaporation is facilitated. Marked surface heating by insolation, which is fairly frequent at high altitudes and occasional in high latitudes, thus often results in abnormally low relative humidities and also in rapid evaporation. The influence of decreased pressure upon evaporation where temperatures are high is illustrated by changes in the boiling temperature of water (a form of rapid evaporation). There is a lowering of 1° F. for each decrease in pressure of about .6 in. (1° C. for 37 mb.). Each rise of 550 ft. (178 m.) produces such a change in average pressure. Water boils, at all levels, at a lower temperature, sometimes as much as 3° F. (1.7° C.) lower, in a Low than in a High.[132]

DISTRIBUTION OF MOISTURE.

54. *The windward sides of continents and of mountain ranges receive much more moisture, and hence more precipitation, than do the leeward sides* because atmospheric moisture is transferred chiefly by the wind. Diffusion is so slow a process that calms of sufficient duration to make diffusion significant are rare. Streams are the only other agent distributing much moisture. Rivers such as the Volga and Nile which carry large volumes of water into arid regions where it evaporates doubtless have some influence on the amount of atmospheric moisture in parts of their basins. The influence of winds on this distribution of moisture is illustrated in many places. For example, in the Hawaiian Islands an average of over 476 inches (12.1 m.) of rain falls annually on Mt. Waialeale, alt. 5075 ft. (1550 m.) on Kauai, while only 16 inches (406 mm.) falls on the leeward slope only 11 miles (18 km.) away. On another island (Maui) two stations only 7½ miles (12 km.) apart receive an average of 369 inches and 18 inches (9373 mm. and 457 mm.) respectively.[133] In the belt of Westerlies the condition near Seattle, Washington is noteworthy. Fifty miles west of Seattle, on the windward slope of the Olympic Mountains, the average precipitation is more than 120 inches (3500 mm.). At Seattle it is only 42 inches (1070 mm.) and an average as low as 18 inches (457 mm.) of rainfall occurs on some of the nearby islands in Puget Sound. Thirty miles east of Seattle, on the western slopes of the Cascades, more than 80 inches (2030 mm.) falls. A

132 Shaw, Meteorological Glossary, p. 300.

133 Summary of Climatological Data for the Hawaiian Section, 1922 and *Mo. Weather Rev.*, Vol. 47, pp. 303-305, 1919.

hundred miles east of Seattle, just east of the Cascades, the average precipitation is less than 10 inches (250 mm.).[134]

55. *The amount of atmospheric moisture (absolute humidity) normally varies inversely with latitude and altitude, and as a rule, directly with distance from the sea,*[135] because absolute humidity increases with the hastened evaporation which is induced by higher temperatures, and because warm air (space) can contain more moisture than cold. Water vapor makes up an average of 2.63% of the surface air at the equator; .92% at latitude 50 N. and .22% at latitude 70 N. The average for the earth is 1.2%.[136] Sometimes water vapor makes up as much as 5% of the weight of the air present over water bodies in warm areas.[137] This is equivalent to a vapor pressure of more than 1½ inches (38 mm.) of mercury. The atmosphere of the warmer half of the globe contains fully four-fifths of the total atmospheric moisture. The average decrease with latitude is illustrated in North Dakota, Nebraska, and Oklahoma, all of which are inland states in the same longitude and with similar amounts of rainfall. The average of the 7 A. M. and 7 P. M. vapor pressures for January, April, July and October is .20 in. (5 mm.) for North Dakota; .25 in. (6.3 mm.) for Nebraska; and .35 in. (9 mm.) for Oklahoma.[138] Decrease in absolute humidity with latitude is also illustrated by the statement that the air over Europe contains on the average enough moisture to yield about an inch (25 mm.) of water if it were all condensed, while condensation of all the atmospheric moisture over the eastern half of the United States would yield nearly 2 inches (50 mm.).[139]

The poleward decrease in vapor pressure is however not at a uniform rate. It varies with the effective distance from water bodies, with average temperatures, and with altitude.[140] In the storm belts, it is probably less than the expected normal for that latitude because the increased upward convection and precipitation in storms tend to lessen the absolute humidity.

Vapor pressure usually decreases inland rather rapidly. It often

---

134 Chart of Average Annual Precipitation in the U. S., Atlas of American Agriculture, 1917. Reprinted in *Mo. Weather Rev.*, Vol. 45, Plate 76, 1917.

135 Day, P. C., Relative Humidities and Vapor Pressures over the United States, *Mo. Weather Rev., Supplement*, No. 6, pp. 5-61 and 24 charts, 1917.

136 Hann, Lehrbuch der Meteorologie, 3rd ed., p. 5, 1915.

137 Day, loc. cit., p. 6.

138 Calculated from data given by Day, *loc. cit.*

139 Day, *loc. cit.*

140 See also Table of Monthly Mean Water Vapor Pressures for Eastern, Central and Central Plateau States for four different latitudes given in *Mo. Weather Rev.*, Vol. 47, p. 772, 1919.

is approximately twice as great along the coast as in the drier portions of the continental interior in the same latitudes. This decrease is due to the fact that the moisture evaporated from the ocean and precipitated inland is not replaced by a like amount evaporated from the land.

The average decrease in water vapor with increase in altitude is sharp. One-half the atmospheric moisture is within a mile (1.6 km.) of sealevel and at six miles (10 km.) the air contains only 1/120 as much as at sealevel.[141] This diminution is chiefly due to the decrease in temperature and hence in capacity, but in part to the fact that the atmosphere is supplied with moisture from below. Indeed all primary evaporation takes place at the bottom of the air.

56. *The absolute humidity is greater by day than at night, greater in summer than in winter and greater during wet periods than during dry periods.* The increase by day and in summer is related to the higher temperatures prevailing. The increased vapor pressure which commonly accompanies wet periods is caused chiefly by the larger supply of moisture from the sea brought inland by the winds. However, the larger amount of surface water and ground water available for evaporation, and actually evaporated, also plays a part.

The average diurnal increase of absolute humidity for the United States amounts to about 15%.[142] The increase is greater in summer than in winter especially if the actual increase and not the percentage of increase is considered. This is because a diurnal range of 30° F. (17° C.), for example, produces a greater change in the amount of moisture held if between 50° F. and 80° F. (10° C. and 27° C.) than if between 0° F. and 30° F. (—18° C. and —1° C.). Furthermore, nocturnal precipitation and dew and frost often greatly reduce the atmospheric moisture at night. In England, a country with high average humidity, the mean diurnal range is about 6%, varying from 5% in December and January to 8% in June and September. Among the months, there is nearly twice as much moisture in the air in July and August as in January and February.[143]

On the average, the vapor pressure is least about sunrise and greatest near mid-day. On the land the maximum comes shortly before noon in all warm places. On the other hand, it comes in the early afternoon in cool places such as the sea, and the land in winter. The normal relationship between absolute humidity and temperature, however, is

141 Humphreys, Physics of the Air, p. 69, 1920.

142 Computed from Day, *loc. cit.*

143 Meteorol. Glossary, *loc. cit.*, pp. 290-292. The monthly and diurnal variations in humidity are clearly presented for Hongkong, in Claxton, The Climate of Hongkong, 1916.

often interfered with by convection. Hence wherever convection is intense, the absolute humidity at the surface of the earth usually is less shortly after mid-day than at any other time, because the warm moist air is then more easily displaced by drier air brought down by convection. In dry regions when convection is strong, there is often a decided decrease in vapor pressure as the hour of maximum temperature and convection approaches, because there is not enough evaporation to replace the moisture carried aloft by intense upward convection. Places, which because of nocturnal "inversion of temperature" have calm nights, may occasionally have more moisture in the surface air in the evening than at 2 P. M.

The seasonal range in absolute humidity depends upon the seasonal change in temperature or wind direction. For places having cold and warm seasons, the maximum occurs in the warmest season and the minimum in the coldest, and there is a difference in humidity corresponding to the contrast in temperature. For example, the vapor pressure in North Dakota averages about nine times as much in July as in January; in Nebraska, six times as great; in Oklahoma four times; in Louisiana 2¼ times; at Key West, Fla., where there is little seasonal contrast in temperature, the vapor pressure of the highest month (August) is .83 in. (21 mm.) whereas in January it is two-thirds as great (.56 in., 14 mm.). These figures indicate also that the annual range in vapor pressure increases with latitude, which is in keeping with the increase in temperature range.[144]

Relative Humidity.

57. *Relative humidity increases, on the average, with latitude and altitude and is greater along the coasts than inland.* In general it increases as absolute humidity decreases. The increase in relative humidity with latitude and altitude accompanies a normal decrease in temperature and hence in capacity for holding moisture. The increase with latitude on the land is illustrated along practically every meridian on Day's maps of relative humidity for the United States[145] in spite of the conspicuous influence of the western highlands on the distribution of moisture. The following annual averages from 7 A. M. and 7 P. M. for places having almost the same precipitation (between 20 and 25 inches) (508-635 mm.) illustrates the influence of latitude: Fargo, N. D., 79%; Huron, S. D., 72%; North Platte, Neb., 70%; Dodge City, Kan., 66%; Abilene, Tex., 64%. Even where the precipita-

[144] Computed from Figs. 4 and 5 in Day *loc. cit.*

[145] Day, *loc. cit.*

tion decreases notably from south to north, as in the following places, the average relative humidity increases with latitude; Chicago, 74%; Milwaukee, 75%; Escanaba, Mich., 79%; also Louisville, Ky., 69%; Indianapolis, Ind., 72%; Grand Rapids, Mich., 76%; and also St. Louis, Mo., 70%; Madison, Wis., 75%. The increase with latitude is made irregular, however, by variations in the distance from the sea.[146] The average relative humidity over the sea is about 85%, while that over the continents is perhaps 60%,[147] ranging from 50% or less in the drier regions to nearly 85% along the coasts. Upon the sea, the normal relative humidity is about 82% in low latitudes and 92% in high latitudes.[148] Relative humidity does not increase normally with latitude between the equator and the centers of the Trade Wind deserts.

The increase in relative humidity with altitude is not rapid and is limited by the cloud zone, above which the air is somewhat drier. The increase is not so great as the temperature gradient would suggest because moisture is supplied only from moist surfaces at the bottom of the atmosphere and there is progressively less and less moist land at higher altitudes. Thus high altitudes often have dry air when saturated air would be expected on the basis of the normal, though often small, increase of relative humidity with altitude. Dryness is much more common on the leeward side of mountains than on the windward side. Such dryness usually is related to a foehn or is produced by an excessive settling of higher layers of air such as often cause the dispersal of clouds at night. (See Law 65.) A third way in which the air at high altitudes is sometimes made intensely dry is given in Law 53 above. This principle operates to make the air dry when in contact with the warm skin. Whenever the cold air of high altitudes and latitudes is warmed by contact with warm skin it becomes distinctly dry and causes rapid evaporation. Thus very cold air affects man like dry air because as it is warmed by contact it becomes relatively dry. This is nearly as true of cold air which was originally saturated as of air which was dry before coming in contact with man.

58. *Relative humidity increases as air ascends and decreases as it descends. Hence relative humidity is greater on windward slopes than on leeward slopes.* This is because the capacity of space for moisture

---

146 In winter in cold regions, the relative humidity often increases inland accompanying the decrease in temperature inland (Hann, Handbook of Climatology, Vol. 1, p. 151).

147 Salisbury, Physiography, p. 495, 1919.

148 Waldo, Elementary Meteorology, p. 127, 1896.

decreases with the temperature. Ascending air is cooled by expansion and by accelerated radiation. Heat lost in these ways is less and less fully replaced at higher altitudes partly because of the increased distance of the air from its chief source of heat,—the surface of the earth,—and because of the interception of heat at lower levels. On the other hand, descending air is warmed by compression and by coming to lower and warmer altitudes. As it is warmed it becomes relatively drier. Under favorable conditions the air becomes warmed conspicuously and is made very dry, producing a foehn.

59. *Atmospheric humidity, both absolute and relative, averages less at the earth's surface in windy areas than in calm areas otherwise similar,* because in windy areas, the moistened lower layers of air are soon mixed with or replaced by drier air from above. Upward convection is the agent which does most to prevent the surface air from being excessively humid. As water vapor is lighter than the other constituents of the surface air, moist air is forced to rise and is replaced by heavier and drier air. The height to which it can ascend is limited by condensation and by gravity. An exception to this rule of decreased humidity with increased windiness often occurs in the centers of Highs, where, in spite of slight windiness, humidity is often relatively low because of descending air.

60. *Relative humidity of the surface air averages greater by night than by day, greater in winter than in summer, greater in cool periods than in hot periods and is also greater before than after precipitation.* The lower humidity by day in summer and during hot periods is related to the higher temperatures and the greater mixing of the surface with the drier air above at those times. The warmest time of the day, year or period normally has the lowest relative humidity because the capacity of the air (space) is greatest then. The highest relative humidity usually occurs at the coldest time. However, the coldest weather of winter in mid-latitudes is not often accompanied by the highest relative humidity because such weather is often caused by a cold wind from higher latitudes or by air descending from somewhat higher altituds, and such air is relatively dry.[149] In general, as the temperature goes up the relative humidity goes down, and *vice versa.* However, after the dew point is reached a further increase in relative humidity is impossible; instead it stays at 100% when the temperature falls still lower.

61. *In general, seasonal and diurnal ranges in relative humidity*

[149] This condition is illustrated locally within the tropics, where the winter winds come from the north, as at Hongkong. See Claxton, *loc. cit.*

vary in harmony with range in temperature, and therefore are commonly great in arid regions and in continental interiors, and small over the sea and most snow-covered areas. Annual range increases toward the equator, with nearness to the ocean or lakes, with aridity, with altitude (up to the cloud zone or snow-line), and with decrease in vegetation. It is also affected by cloudiness and windiness. The amplitude is several times greater on clear than on cloudy days and it is especially small on continuously rainy days. The range is smaller when the wind blows steadily than in times of fitful winds or calm. The increase in relative humidity before precipitation is sufficiently marked in many places to be useful in forecasting the weather.[150] Several of these kinds of variation in relative humidity are illustrated by the following figures, from Day's tables.[151] At Burlington, Vt., the average winter (December, January and February) maximum (about sunrise) and the average winter minimum (about 2 P. M.) are 79% and 67% respectively; in summer (June, July and August) 84% and 53% respectively; at St. Louis, Mo., the corresponding figures are 74% and 54% (winter) and 71% and 50% (summer); at Sheridan, Wyo., 84% and 56% (winter) and 82% and 37% (summer). Waldo gives the diurnal amplitude for the northwestern coast of Europe as 7% in December and 17% in August; for Nukuss in central Asia, 26% in December and 50% in summer.[152]

Abnormally low relative humidities occur occasionally in the surface air. Such departures are much more extreme over the land than over the sea and in dry regions than in wet. In arid regions in the United States humidities as low as 3% occasionally occur and in humid regions as low as 10%.[153] Abnormally low relative humidities are caused by a sharp rise in the temperature of the affected air. In rugged areas, foehns often cause extreme dryness. Perhaps the free-air foehn[154] is not rare in connection with cyclonic storms. The intense downward movement produces the relative dryness.

CONDENSATION.

62. *As condensation occurs whenever air is cooled below the satura-*

150 Garriot, E. B., Weather Folklore and Local Weather Signs, *U. S. Weather Bureau, Bull.* 33, pp. 20-22, 1903.

151 Day, *loc. cit.*, pp. 13-61.

152 Waldo, Elementary Meteorology, p. 125, 1896.

153 Day, *loc. cit.*, p. 10. At Hongkong, where the average rainfall is 83 in. (2110 mm.) relative humidities as low as 5% have been recorded in winter. (Claxton, *loc. cit.*)

154 Brooks, C. F., A hill-top foehn, *Mo. Weather Rev.*, Vol. 47, p. 567, 1919.

tion point, it is most frequent at night and in winter, except such as is due to convection which is most frequent when convection is most intense, namely during the day and in summer, over the land. Nocturnal and winter cooling sufficient to cause condensation is due chiefly to chilling induced by loss of heat by radiation from the surface to the overlying air, or from the air downward to colder land or water. Loss of heat by conduction is important where good conductors are involved. Condensation is sometimes caused by the mixture of cold air and warm air, as when a cold wind is blowing over warm water. Most clouds are caused by convection. Ascending air is cooled by expansion at the rate of 1.6 degrees F. for each 300 feet of ascent (1° C. per 103 meters), until condensation occurs.[155] Dew, frost and fog usually appear by night and disappear by day, because of the diurnal range in temperature and in relative humidity. (For clouds see Law 65, beyond.) The greater frequency of condensation in winter is illustrated at Chicago, where, in spite of the fact that much more rain falls in summer than in winter, precipitation is 30% more frequent in winter than in summer.[156]

63. *The frequency of condensation tends to increase with latitude, with humidity and with altitude,* up to the cloud level. Except where deserts are involved, cloudiness increases with latitude, though in high latitudes the clouds commonly are thin. Sealevel fogs often persist throughout the day in high latitudes, but not in low latitudes. Frost also frequently does not disappear by day in high latitudes while dew practically always disappears by day in low latitudes. Snow and rain disappear slowly in the higher latitudes. The frequency of dew and frost formation tends to increase in any latitude with increase in diurnal range. Dew seldom forms on shipboard at sea. In arid regions the relative humidity often is so low that condensation does not occur even when the diurnal range is great. The persistence of frost or fog by day in high latitudes is greatest where the diurnal range is small, as over snowfields or on the sea.

64. *The amount of condensation decreases, on the average, with latitude, except in the Trade Wind deserts, and also with altitude above a few thousand feet.* The amount of condensation depends on the absolute humidity of the air, the amount of vapor cooled, and the extent of cooling. In the rainy tropics, where the absolute humidity is great, as much as one-tenth of an inch (2.5 mm.) of dew gathers

155 Humphreys, Physics of the Air, p. 31, 1920.

156 Cox and Armington, The Weather and Climate of Chicago, p. 168, 1914.

during some nights.[157] In mid-latitudes a hundredth of an inch is a heavy dew. Clouds generally decrease in thickness and density with increase in latitude and with increase in altitude above three thousand feet (900 m.). In high latitudes the sun or moon can often be seen through clouds. Indeed, in polar regions it often snows from an almost clear sky.

The normal relationship between latitude and condensation is disturbed by the distribution of atmospheric dust. Cities, with their vast quantities of soot and hygroscopic dust, are sites of undue condensation, and their air nearly always has more haze than is normal for the latitude. In many cities the persistent haze is called smoke, and in others, in cool moist climates, it is often a fog. This is due chiefly to the condensation upon atmospheric dust which is a better radiator than air, and thus often cools below the dewpoint. In moist regions condensation upon the cold dust particles frequently occurs, and thus the dust acts as nuclei of fog particles. If dust particles suitable to serve as nuclei are not present in sufficient abundance, considerable super-saturation may precede condensation. In nature, however, there apparently is always sufficient dust present.[158]

65. *The amount of condensation varies from time to time with variations in the intensity of temperature changes and with the humidity.* Hence dew and frost form most abundantly when the nocturnal cooling is rapid. Because of the lessened absolute humidity following condensation, the rate of dew and frost accumulation normally declines soon after the dew-point is passed. This often occurs early in the evening. There is also a marked diurnal variation in the amount of cloudiness.[159] However, as clouds are usually formed by convectional cooling rather than by cooling by radiation, the amount of condensation represented by clouds tends to vary with convection. Therefore cloudiness usually increases by day whenever convection is marked because convection increases until the warmest time of the day is reached. Upward convection often brings bodies of air to heights where the saturation point is passed. After normal convection has reached its maximum, which commonly occurs between 2 and 3 P. M., cloudiness may increase for a time because of further cooling of air brought almost to the dew point by convection. This continued cooling is facilitated by the lessened insolation which accompanies the decrease

157 Von Bezold, Wm., in Abbe, C., Mechanics of the Earth's Atmosphere, *Smithsonian Misc. Collect.*, p. 283, 1893.

158 Shaw, W. N., Law of Saturation, *Mo. Weather Rev.*, Vol. 42, p. 198, 1914.

159 Cox and Armington, *loc. cit.*, p. 260.

in the angle of incidence and the development of higher clouds. The sky often clears at night because of the descent of the clouds instead of becoming overcast as would be expected where the nights are cool. At night, when convection largely ceases, the clouds are pulled downward by gravity. Often when once they are descending relatively rapidly, inertia prevents their stopping until they are sufficiently warmed dynamically to evaporate the condensed moisture. The fact that the higher air is often warmer at night than the surface air, because free air cools slowly, is also of importance in this connection. The amount of condensation to form clouds also tends to vary directly with the intensity of convection according to the season. This is true in spite of the fact that the percentage of cloudiness commonly is greater in winter, when convection is least, than in mid-summer when it is greatest.[160] Winter clouds, however, are normally at low altitudes and relatively thin, their volume and mass being usually less than that of the scattered clouds of a partly cloudy summer day. In summer, when the sun is high its rays often penetrate an amount of condensed moisture sufficient to form what in winter would appear to be a cloud-cover.

PRECIPITATION: KINDS OF.

66. *Precipitation varies in kind from place to place.* While perhaps four-fifths of the world's precipitation is in the form of rain, yet in high latitudes and altitudes, snowfall is important. Moreover sleet and hail have considerable significance. In respect to rainfall, notable differences in size of drops and in intensity of fall occur. Sleet is relatively of most importance in cyclonic climates in coastal regions in fairly high latitudes. Hail, which is always associated with intense convection, is probably most frequently formed in low latitudes. However, as a result of the rapid melting during descent relatively little hail reaches the ground in tropical lowlands. Hence hail is most frequently experienced in latitudes 20°-40°, although it falls in considerable quantities in lower latitudes. For example, ten hailstorms of a destructive character were reported in a decade in latitudes 13°-16° S. near sealevel in Australia and three hailstorms occurred in Panama (latitude 9°) in a 12-year period.[161] On the other hand, several local hailstorms occur each year in subtropical Australia,[162] and in south eastern United States.

---

[160] *Ibid.*, p. 267.

[161] Visher, S. S., Hail in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 117-118, 1922.

[162] Commonwealth Bureau of Meteorology, Charts of Hail Storms, Melbourne, 1913-18.

The smallest average sized raindrops probably occur in cool marine climates where the normal precipitation is a drizzle.[163] The size of characteristic drops increases in general toward the equator and with increased aridity accompanying a similar increase in the intensity of convection. As to the rate of fall, the heaviest rains occur in low latitudes, and in general there is a progressive decline poleward in the maximum rainfall received in a day or an hour.[164] This decline is due chiefly to a similar decrease in intensity of convection as is illustrated by the lesser frequency of thunderstorms.[165]

67. *Most places experience seasonal variations in the kind of precipitation.* Snow often falls during the winter in middle and high latitudes, while rain often falls even in polar regions in summer.[166] Hail is characteristic of the season of most intense convection, which, for all but a few points, is shortly after the period when the sun is most nearly overhead. In respect to rainfall, there normally is a seasonal variation in size of drops, in intensity of downpour and in the velocity of fall. Winter rain commonly is made up of smaller drops than summer rain, and falls more slowly and more steadily. Downpours and "cloudbursts" are to be expected at the time of most intense convection.

PLACE DISTRIBUTION.

68. *Precipitation normally is heavy on the windward slope of steep high or cool mountains in relatively warm regions* because wherever a large volume of warm moist air is cooled notably below the saturation point, much condensation occurs (See Law 54). Rapid cooling of warm air is also often accomplished by rapid convectional ascent, where insolation is intense and therefore thunderstorms yield much rain. Precipitation is much less heavy when cold air is further cooled. Hence in uniformly cold regions, mountains have much less effect than in warm regions. The steepness of the slope is significant because convectional overturning is often induced by rather low elevations possessing a steep slope on the windward side.[167] Minor causes of air

163 In Netherlands, for example, four days of each normal week are classed as rainy and yet only 28 inches (711 mm.) is received in the entire year. (Kan, C. M., in Mills International Geogr., p. 219, 1907.)

164 For the United States, see charts of maximum rainfall in 24 consecutive hours and in one hour, *Mo. Weather Rev.*, Vol. 50, p. 119, 1922.

165 *Ibid.*, p. 122, Distribution of Thunderstorms in the United States.

166 Stefansson, V., The Friendly Arctic, 1921.

167 The importance of the inclination of the slope is emphasized by Pockels, F., Precipitation on Mountain Slopes (1901) translated in C. Abbe third series of the Mechanic of the Earth's Atmosphere, *Smithsonian Collections*, No. 1869, p. 101, 1910.

cooling are chilling by a cold wind, and contact with a cold surface (without ascent). Drizzles and fogs are often formed in these ways. The heavy precipitation in the doldrum belt and by thunderstorms elsewhere, the rainy character of the windward slopes of mountains in the Trade Wind belts and elsewhere, are all illustrations of this law.[168]

69. *Precipitation decreases irregularly in amount with increase in latitude, and in effective distance from the ocean.* The average precipitation for the globe is about 20 inches (508 mm.). The heaviest rainfall on the land of any entire latitude is in the doldrum belt (80 inches (2000 mm.) or more), and the least normal precipitation is perhaps in the polar regions (less than 10 inches; 250 mm.). While the Sahara and many other parts of the Trade Wind belts receive no more precipitation than do the polar regions, the average for the Trade Wind belts is raised notably by the precipitation received on the windward slopes, as is illustrated in Law 54 above. The scanty precipitation in polar regions, as at high altitudes, is due largely to the small amount of moisture in the cold air, but the slight convection there is also a factor. The poleward decrease in precipitation is illustrated on all continents.[169] The decrease with latitude is at a higher rate on the continents than on the ocean, for although in the tropics more rain falls on the land than on the sea, the reverse is true in high latitudes.[170] Not only is there a decrease in total rainfall, but there is a corresponding decrease in intensity. In Australia, for example, the number of days on which 5 inches (127 mm.) or more of rain has fallen, decreases steadily and sharply poleward.[171] The same occurs in the United States[172] and elsewhere, except where east-west mountain ranges, such as the Himalayas, form complicating factors by causing marked condensation. All the records of 30 inches (760 mm.) or more of rainfall within 24 hours are from tropical latitudes, as are nearly all records of falls in excess of 10 inches (254 mm.) in 24 hours.[173] In the United States, for example, in twenty years the only areas receiving over 10 inches (254 mm.) in 24 consecutive hours were along the Gulf Coast. No area in the northern third of the

---

168 See Laws 54 and 71 for concrete illustrations.

169 See Herbertson's rainfall maps in Bartholomew's Physical Atlas, 1899.

170 Moore, John, Meteorology, p. 223, 1910 (quoting Herbertson).

171 See lists of heavy rainfalls, Hunt, H. A., The Climate and Meteorology of Australia, Official Yearbook, pp. 59-63, 1920.

172 See Precipitation Section of Atlas of American Agriculture (partly reproduced in *Mo. Weather Rev.*, Vol. 50, pp. 117-124, 1922.

173 Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly*, Vol. 15, pp. 28-31, 1922.

country received over 6 inches (150 mm.) while nearly five-sixths of the northern border had an extreme maximum of less than 4 inches (100 mm.).[174]

70. *Precipitation increases with altitude to moderate heights and then decreases steadily and sharply until at the height of 2 or 3 miles (3-5 km.) it is slight.* The maximum precipitation on steep mountains takes place at an elevation of about 3300 ft. (1000 m.) in the tropics, and about 4500-5000 ft. (1370-1520 m.) in mid-latitudes.[175] The altitude of the zone of maximum precipitation depends upon the relative humidity and temperature of ascending air. Therefore the height fluctuates with the seasons, being lowest in winter, when low temperatures cause prompter precipitation, than in summer when the relative humidity at any given level is less than in winter.[176] The rate of increase up to the zone of maximum rainfall varies with the total rainfall, being 100 in. for each 1000 ft. (830 mm. per 100 m.) for example, in portions of the Himalayas, 40 in. per 1000 ft. (333 mm. per 100 m.) in Java, and only 2 in. per 1000 ft. (17 mm. per 100 m.) in arid portions of Africa and South America.[177] However, when expressed in percentages, the rate of increase is somewhat similar even in such diverse cases as these, for the increase with each 1000 or 1500 ft. (300 or 450 m.) of altitude is approximately equal to the total rainfall at the base of the slope. Above the zone of maximum rainfall, the decrease is rapid. At high altitudes, it is chiefly in the form of "finely pulverized snow or a drizzle."[178]

71. *Local contrasts in the amount of rainfall are greater in tropical than in higher latitudes among topographically similar places, with the exception of the doldrums.* Local contrasts in humidity, evaporation and wind likewise commonly decrease with latitude. It is probable that tropical, mountainous, oceanic islands have the greatest local climatic differentiation while polar regions have the least. Near the poles even a high mountain causes relatively little local differentiation. In low latitudes one side of many moderate elevations is distinctly more humid than the opposite side, and there is a sudden change in humidity and precipitation with altitude even on the windward slope. Both wind direction and altitude influence the rainfall of many small

[174] Precipitation Section of Atlas of American Agriculture, *loc. cit.*

[175] Henry, A. J., Increase of Precipitation with Altitude, *Mo. Weather Rev.*, Vol. 47, pp. 33-41, 1919. On mountains which rise from dry plateaus, however, the zone of maximum precipitation is considerably higher than these figures.

[176] Hann, J., Lehrbuch der Meteorologie, 3rd ed., 1915.

[177] Henry, *loc. cit.*, p. 34.

[178] Hann, Lehrbuch, quoted by Henry, *loc. cit.*

areas. For instance, within the city of Honolulu the average rainfall ranges from less than 25 in. (635 mm.) to over 90 in. (2290 mm.) at a place of similar elevation only 5 miles (8 km.) distant. Also within 4 miles (6 km.) of the central station with its 31 in. (790 mm.) of rain there is a station with an elevation of 1360 ft. (414 m.) and an average rainfall of 106 in. (2700 mm.). On another of the Hawaiian Islands, Kauai, apparently the rainiest official rainfall station on the globe and with an average of over 476 in. (12.2 m.), is 11 miles (18 km.) distant from a station which receives less than 20 in. (508 mm.).[179] In middle and high latitudes there normally is relatively little contrast in rainfall between the sides of single ranges since the winds come into cyclonic depressions from all directions in turn, instead of chiefly from one direction as in the tropics. Hence one side normally is very dry in higher latitudes only in case the winds are prevented by some other range from bringing moisture to it. Consider the relatively slight contrast in rainfall on the different sides of the Appalachians, Alps and Caucasus, in comparison with the great contrasts found on most tropical ranges. The local change in rainfall, which accompanies change in altitude, also is less in higher latitudes than in low because there is less change in capacity for moisture when cool air is further cooled than when warm air is cooled a like amount by being forced to rise.

Other causes of greater local differentiation in climate in low latitudes than in high are (a) the steeper vertical temperature gradient, so that corresponding changes in altitude produce greater changes of temperature in the tropics than in high latitudes, especially at night, (b) the greater tendency for calms to develop on lowlands at night in the tropics than in higher latitudes (See Law 48, under winds). It is partly for this reason that even moderately low ridges in the tropics have an appreciably different nocturnal climate from nearby plains, while there is less differentiation between ridge and plain in higher latitudes. (c) A third factor which causes greater local contrast in low than in higher latitudes is the sea breeze, which is much commoner in warm than in cool regions, and which gives to a narrow littoral strip in the tropics a climate distinctly different throughout the year from that found only a short distance inland. Sea breezes blow almost every day upon many tropical coasts because the land becomes very much warmer than the water almost every day, instead of only during hot spells in summer, as in high latitudes. Other sorts

179 Climatological Data, Hawaiian Section, 1922, supplemented by annual reports for 1919-21 inclusive.

of climatic localization and their chief causes are discussed more fully elsewhere.[180]

Diurnal and Seasonal Distribution.

72. *Precipitation takes places more easily in winter than in summer and at night than by day* because precipitation occurs whenever drops, flakes or pellets are formed which are too heavy to be sustained in the air by the rising air currents. Such ascending currents are weaker in winter and at night than in summer and during the day. Precipitation reaches the surface whenever the particles are not evaporated as they fall. Much summer rain, especially above deserts, fails to reach the earth. Hence additional reasons why precipitation reaches the surface more readily in winter than in summer, and also more easily at night than by day, are because the clouds are usually lower and the lower air is more humid in the cooler than in the warmer times. Ease of precipitation does not however imply amount of precipitation, for in spite of the fact that precipitation is often induced in winter by barometric influences which would not yield precipitation in summer,[181] the total amount of precipitation received in summer is greater than that received in winter over a large share of the earth. One result of the greater ease with which precipitation takes place in winter than in summer is the fact that snow storms normally last longer than rainstorms, in spite of the fact that cyclonic storms usually move more rapidly in winter than in summer.[182] At Chicago, the average snow storm lasts 7.5 hours while the average rain storm lasts 3.9 hours.[183]

73. *Most places have a wet season and a dry season* because the distribution of precipitation throughout the year depends on (1) comparative temperature of land and sea, (2) wind direction and character, (3) intensity of insolation and hence of convection, (4) frequency of temperature changes passing the dew-point. When land is notably cooler than the sea, precipitation on the land is to be expected if the wind is off the sea. In such a wind, the air in contact with the colder land surface is cooled by radiation and conduction. Another part is cooled by being forced to rise over air piled up by the much greater friction on land than on the sea. However, the rise produced in this way is seldom sufficient in itself to cause heavy precipitation. Cyclonic

180 Visher, S. S., Local Climates in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 119-121, 1922.

181 Henry and others, Weather Forecasting in the United States, *loc. cit.*

182 *Ibid.*

183 Cox and Armington, *loc. cit.*, pp. 185-191.

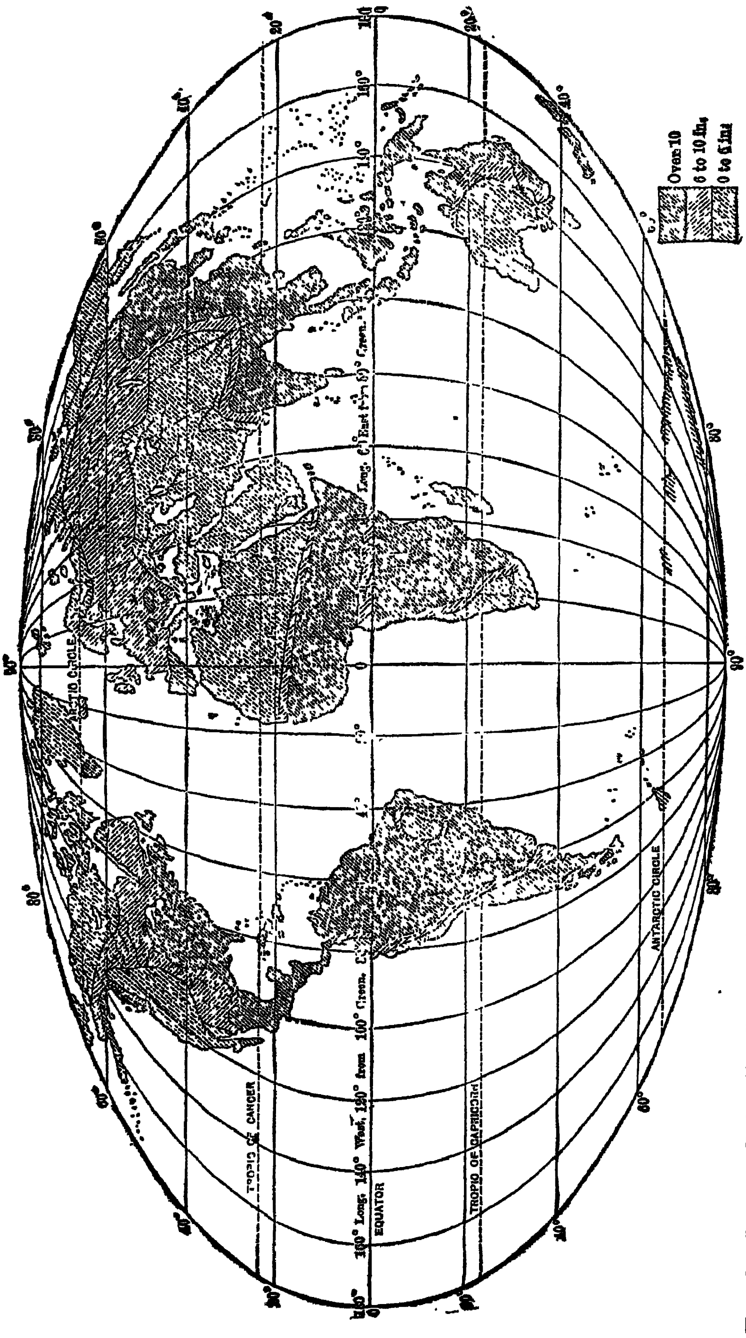


Fig. 6.—Summer Rainfall. June to August, North of Equator—December to February, South of Equator. (From Huntington and Williams' Business Geography, after Supan.)

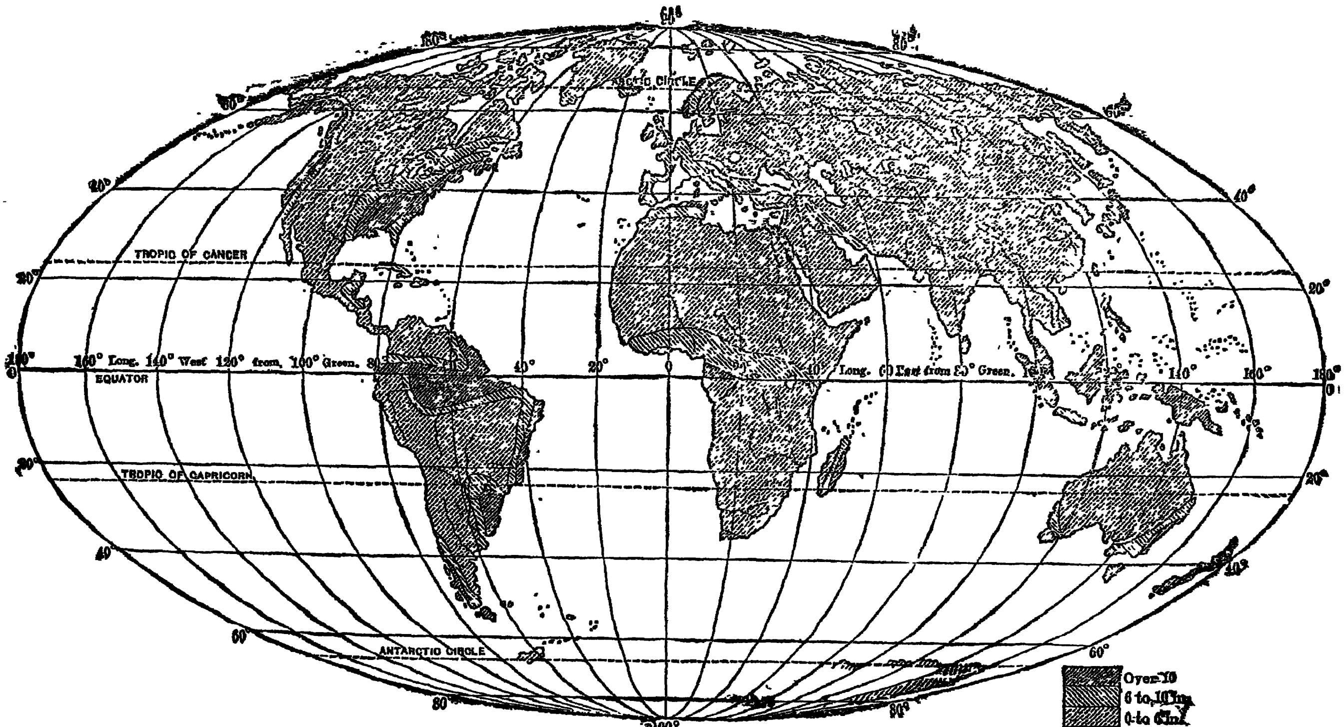


FIG. 7.—Winter Rainfall. December to February, North of Equator—June to August, South of Equator. (From Huntington and Williams' Business Geography, after Supan.)

and irregular winds bring more precipitation to most plains than do steady winds. Intense insolation normally produces active evaporation, strong convection currents and subsequent thunderstorms. Variations in temperature from above the saturation point to those notably below that point cause precipitation.[184]

The season during which an area normally receives the most precipitation depends upon which of the four influences enumerated above is most significant. In general the warmer regions receive most of their precipitation shortly after the date when the sun is overhead or most nearly so, because of the intensified convection. Cold regions also receive most precipitation in their warmer season because during their colder season the air can contain little moisture and hence can give up little. Furthermore, there is little moisture available for precipitation in cold areas because winds blowing toward them have lost much of their moisture before going far inland. The shifting of the wind belts with the seasons is the dominating influence in seasonal rainfall variations for many subtropical and subequatorial areas. The winter season is the wet one on western coasts in the subtropical belt. Interior plains in mid-latitudes have more precipitation in spring and early summer than in any other four or five months.[185] Raininess in spring is a result of (1) the release of moisture accumulated on and in the ground during the winter, (2) the changeableness of the temperatures and (3) the steep temperature gradient upward. The summer rains result chiefly from increased convection and frequent reprecipitation and especially from the indraught of moisture-laden air from the sea, induced by high continental temperatures. Between the spring and the summer rains there is often a drought, frequently in June in mid-latitudes in the northern hemisphere. Winter droughts in continental interiors are due in part to the faster movement of the Lows at that season but chiefly to the fact that condensation then takes place nearer the coast than it does in summer, because of the rapid fall in temperature inland from the coast in winter.

74. *The seasonal range in rainfall varies with latitude and with relation to the ocean.* The contrast between the amounts of precipitation received in the wet season and in the dry is greater in the tropics than in middle latitudes. Indeed it seemingly varies inversely with the latitude from the edge of the doldrums to the polar regions, among places otherwise similar. The range also normally increases from the

[184] Unless such temperatures are confined to the air in contact with the surface of the land, when dew or frost formation occurs instead of precipitation.

[185] For maps of the season of rainfall see Bartholomew, *loc. cit.*

coast inland, and it probably averages less on windward than on leeward coasts. The average increase inland is largely due to the scanty winter rainfall characteristic of continental interiors. (See preceding law.) On the average windward coasts have less range than leeward coasts because the latter get a large share of their moisture from cyclonic winds which are less regular in occurrence and strength than the planetary winds. However those portions of the lee coasts which experience strong monsoons normally have well defined wet and dry seasons. Evidence showing the greater seasonal contrast in rainfall in low than in middle latitudes is given elsewhere.[186] Briefly, much more of the tropics possesses a large contrast among the monthly totals of rainfall than is the case in middle latitudes. For example, twice as large a percentage of their area receives 20% more rain in the wettest than in the driest month. In respect to greater and lesser percentage ranges also, the tropics are inferior to the higher latitudes. The great seasonal range in the low latitudes is related to the fact that most tropical localities are crossed by desiccating winds during part of the year (the Trades or land monsoons), while in other months conditions are favorable for rain, as when the doldrums pass, or when the ocean monsoon prevails, or in Mediterranean climates, when the Westerlies prevail. In higher latitudes rainfall conditions are on the average more uniform throughout the year, not only because of the general lack of drying winds, but also because there is greater uniformity in the effects of cyclonic disturbances. (See Law 80.)

75. *The frequency of precipitation tends to increase directly with the annual amount but inversely with the monthly range in precipitation* except in the monsoon areas. In other words, places with heavy rainfall are usually places of frequent rains, and wet years are years of many rainy days, on the average. However, in regions of marked seasonal distribution of rainfall, precipitation occurs fewer times in a year than in places where rainfall seasons are less marked. Since in general the seasonal range is greater in low than in high latitudes, the frequency of rain tends to be less in low latitudes than in high, wherever similar annual amounts are received. However, on windward slopes in the Trade Wind belt the frequency is high as is also the annual amount, while the monthly range is comparatively low.[187] A

---

[186] Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly,* Vol. 15, pp. 23-35, 1922, and The Variability of Tropical Climates, *Meteorol. Mag.,* London, Vol. 58, pp. 121-125, 154-159, 178-179, 1923.

[187] See Supan: Bartholomew's Physical Atlas: Meteorology, p. 19, 1899.

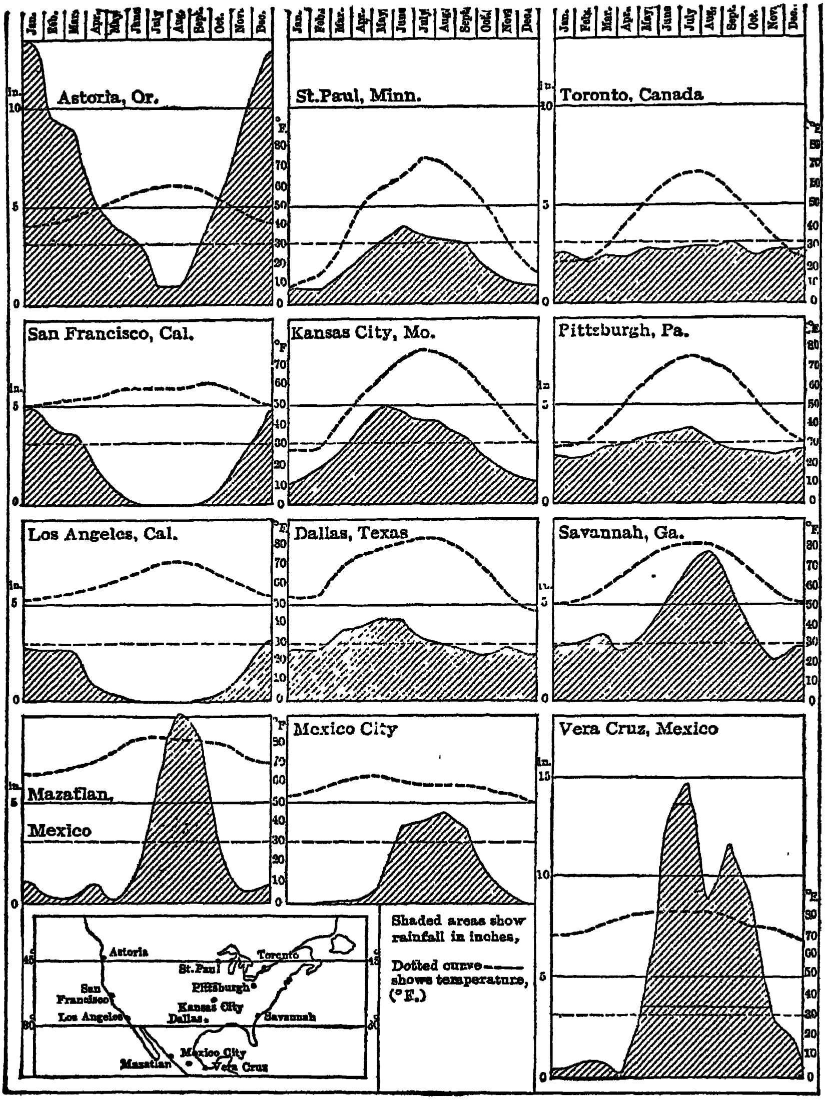


FIG. 8.—Average Monthly Temperature and Rainfall of Cities in North Ameri
(From Huntington and Cushings' Principles of Human Geography.)

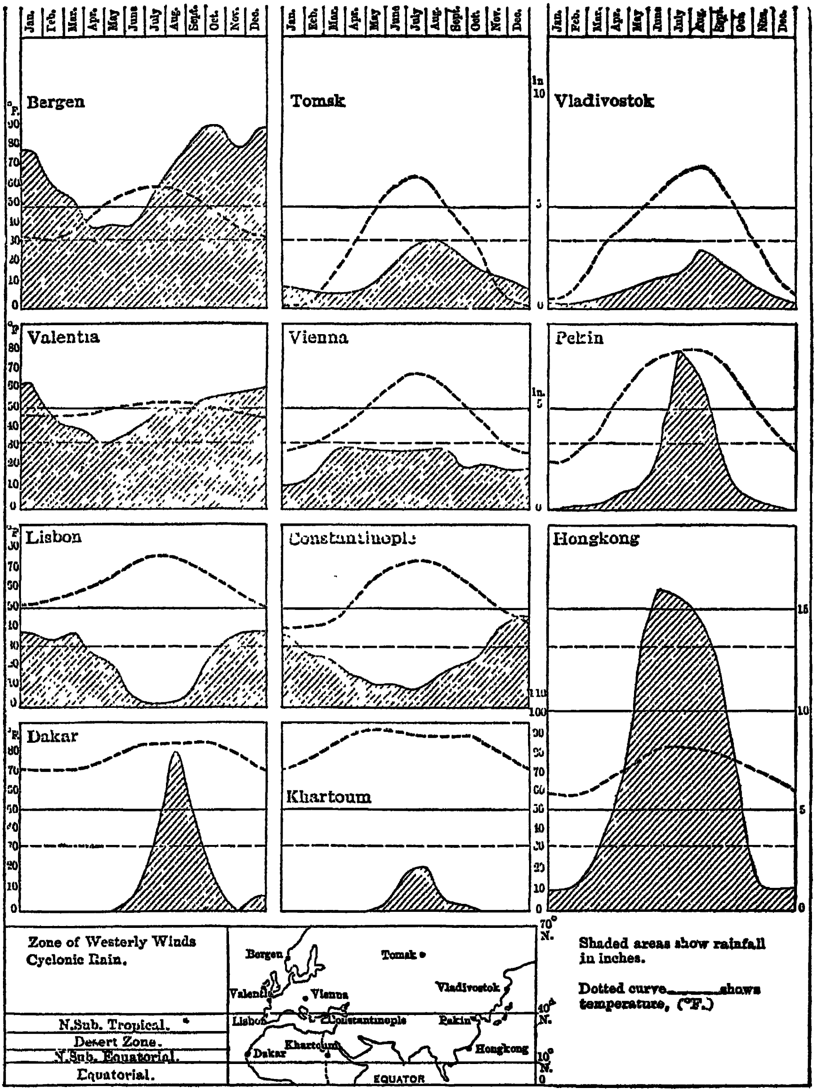


FIG. 9.—Average Monthly Temperature and Rainfall of Representative Places in the Old World. (From Huntington and Cushings' Principles of Human Geography.)

special illustration of the frequency of precipitation is the duration of rainfall, which increases with the latitude.[188]

76. *There are for most places two diurnal maxima and two minima for precipitation in regard to both amount and frequency. The maxima usually are at 2-5 P. M. and 3-6 A. M., and the minima at 9-12 A. M. and 11 P. M.-2 A. M. respectively.* The afternoon maximum coincides with or follows the period of most intense convection. Sometimes the afternoon maximum is delayed until early evening. The early morning maximum is caused by the marked turnover which often occurs then as a result of the excessive cooling of air above the surface layers. The forenoon minimum and the midnight minimum occur at times when heating and cooling respectively are taking place steadily but have not gone far enough to cause marked convection or overturning.[189]

There is considerable variation from place to place, and also from season to season in the precipitation yielded by the nocturnal and afternoon maximum. In the southeastern part of the United States, and in the arid west, much more rain is received from the afternoon maximum. Indeed nocturnal rain is relatively uncommon there. In the Northeastern States, on the other hand, while the afternoon maximum predominates, it yields only a little more rain than the nocturnal maximum. A different condition prevails over a considerable area in the central part of the United States, for there more summer rainfall is received between 8 P. M. and 8 A. M. than in the other 12 hours. In the center of this area, southern Nebraska, the "nocturnal" precipitation makes up 65% of the total.[190] In the British Isles more rain falls at night than by day during the winter and the reverse is true in summer, though this condition is partly due to the corresponding seasonal difference in the length of day and night.[191] In the rainy tropics, although rain is very common from 3-6 A. M., afternoon showers are expected daily.[192]

VARIABILITY.

77. *Variability in the amount of precipitation increases with aridity,*

---

188 Hann, *loc. cit.*, p. 61.

189 For discussion of diurnal distribution of rainfall see Hann, Lehrbuch, *loc. cit.*, pp. 338-346; and Cox and Armington, *loc. cit.,;* and Claxton, *loc. cit.*

190 Kincer, J. B., Day-time and Night-time Precipitation (in the U. S.) and their Economic Significance. *Mo. Weather Rev.*, Vol. 44, pp. 628-632, 1916. A summary of this paper with interpretations is given by Humphreys, *Ibid*, Vol. 49, pp. 350-351, 1921.

191 Moore, Sir John, Meteorology, p. 262, 1910.

192 Ward, Climate, *loc. cit.*, p. 82.

because, (1) the chances of a constant supply of atmospheric moisture reaching an area decreases with an increase in the remoteness of that area from its source of moisture. Little moisture is carried in one continuous journey from the ocean to any moderately inaccessible point and precipitated there. Instead most moisture is precipitated and evaporated repeatedly, and sometimes it is carried away from the ocean and sometimes toward it by the winds and streams. In its journey toward the drier regions, the total supply of moisture is decreased by runoff. (2) In humid regions a considerable portion of any excess rainfall returns to the sea as runoff, whereas in arid or semi-arid regions an unusually heavy, widespread rainfall may disturb the normal moisture conditions for a considerable period. (3) The abundant soil moisture, dense vegetation, high water-table and standing water present in humid regions act as a stabilizer of atmospheric moisture conditions, whereas the relative lack of these influences in more arid regions permits greater variations in moisture conditions.[193]

78. *The amount of precipitation received by an area during corresponding intervals of time varies irregularly.* One summer or year may be wet and the next dry, or several wet years may be followed by several dry ones. Most fluctuations in precipitation in middle latitudes are related to differences in the paths, the intensity, the speed and the size of Lows, for these cyclonic disturbances cause most of the rainfall. Storm tracks are affected by anomalous variations in the temperature of continental and oceanic areas. Lows often tend to move toward abnormally warm areas. The rainfall in low latitudes, as well as in middle latitudes is closely related to the passage of low pressure areas.[194] A special feature of the irregular fluctuations in the amount of precipitation is the tendency for wet periods to perpetuate themselves, and for droughts to continue. This is perhaps never a dominating influence but undoubtedly is sometimes significant. Abundant surface waters and a high water-table certainly are more conducive to a high atmospheric humidity than are parched soil and dry lakebeds. Conversely, "All signs of rain fail in dry weather." The importance of soil and surface water in supplying moisture for precipi-

193 Visher, S. S., Rainfall in the Great Plains in The Geography of South Dakota, *loc. cit.*, pp. 60-67.

194 Taylor, G., The Australian Environment especially as controlled by rainfall, 1918 (summarized by Visher in *Mo. Weather Rev.*, Vol. 47, pp. 490-494, 1919), and Visher, S. S., Australian Hurricanes and Related Tropical Cyclones, *Bull. Commonweath Bur. of Meteorol.*, 1923; for the U. S. see Henry and others, Weather Forecasting in the U. S., *loc. cit.* and especially Henry, A. J., Secular Variation of Precipitation in the United States, *Bull. Amer. Geogr. Soc.*, Vol. 46, pp. 192-201, 1914.

tation is suggested by Murray's estimate that only one-fourth or one-fifth of the precipitation on the land is returned to the ocean by the rivers.[195] In some level areas the proportion of runoff is much less; for example it is only about one-twentieth for the basin of the Red River of the North. If three-fourths or more of all the precipitation on the land is evaporated locally, as seems likely, much of it probably is reprecipitated on the land. Areas remote from the ocean probably receive much more than half their precipitation in this way.

79. *Cycles of rainfall occur in many places.* Many of these are quite irregular in length and in intensity and no doubt many are due largely to the semi-periodic return, called for by the law of chance, of similar combinations of atmospheric conditions, as when analogous storms travel along similar paths. However a part of the semi-periodic fluctuation appears to be related to variations in the activity of the sun, for a correlation between sunspot periods and fluctuations in precipitation seems to be established.[196] In general continental interiors receive more rainfall when the sunspots are increasing than when they are decreasing, whereas marine climates and some others, respond in the opposite way. The fact that different areas respond in opposite ways to changed solar activity has done much to conceal the relationship between solar changes and terrestrial weather, for wherever the rainfall of large regions are compared, the excessive rainfall received in one part may offset the deficient rainfall of another part. Another disturbing practice has been the comparison of the rainfall records of the single year when the sun's spottedness reached the maximum with the records of the single year when the spottedness was at a minimum. It is a well established fact that a single year is not so good a basis for comparison as the average of a number of years. When the rainfall data for the several years of increasing spottedness are compared with those of the years of decreasing spottedness, rather sharp contrasts become evident, which can be explained fairly well by shifts in the average storm paths, and by variations in the storms themselves.[197]

The anomalous temperature and pressures which develop from time

---

195 Quoted by Tarr-Martin, Physiography, p. 104.

196 Brooks, C. E. P., The Secular Variation in Climate, *Geogr. Rev.*, Vol. 11, pp. 120-137, 1921; and Clements, F. E., Drought Periods and Climatic Cycles, *Ecology*, Vol. 2, pp. 181-188, 1921. See however a review and discussion of Clement's paper by Henry, A. J., *Mo. Weather Rev.*, Vol. 50, pp. 127-131, 1922.

197 For a summary of evidence concerning changes in precipitation see Huntington, Earth and Sun, 1923 and Huntington and Visher, Climatic Changes, *loc. cit.*, pp. 53, 58, 59 and 93.

to time over critical portions of the ocean and land are quite possibly induced indirectly by variations in solar activity. As noted in the previous law, storm paths are strongly affected by the development of such abnormal conditions. Likewise there appears to be a general shift in storm paths within the sunspot cycle. When the sun is increasing in activity, the main storm track shifts poleward,[198] with resulting changes in rainfall in a rather wide though not straight belt. The character of the change differs, however, within this belt, for at the same time that the rainfall is increasing toward the northern margin, it is decreasing at the southern.

80. *Dependability of rainfall is greater in middle than in low latitudes, and tends to increase with latitude, among places receiving similar amounts.* Most tropical cities, concerning which data are available, received three or more times as much rain in an especially wet year as in an especially dry one, while in mid-latitudes, few places receive twice as much. Indeed in fairly high latitudes in western Europe the range seldom is as great as 50%. This decrease in absolute range is the more notable because it accompanies a general decrease in total rainfall. With the smaller total annual amounts of precipitation characteristic of high latitudes, it is easier to obtain large percentage ranges than it is with the larger totals characteristic of low latitudes. Many illustrations of widespread and marked fluctuations in annual rainfall in tropical regions are given elsewhere.[199] A few may be mentioned here. The average rainfall at the 150 rainfall stations scattered over the Hawaiian Islands was 54.5 inches (1284 mm.) for 1918 but was 112.9 inches (2868 mm.) for 1919. Equatorial Singapore has received five times as much rainfall in one year as in another; equatorial Oceanic Island (longitude 169° E.) received 8 times as much rain in 1905 as in 1909 (19.6 inches vs. 158.9 inches; 500 mm. vs. 4040 mm.); Malden Island (latitude 4° S., longitude 155° W.), 2,000 miles (3220 km.) to the eastward, received 16 times as much in 1905 as in 1908 (3.9 in. vs. 63.4 in.; 99 mm. vs. 1610 mm.).

Not only is there a wider range in the annual rainfall in low latitudes, but excessive falls within short periods are of greater magnitude and are more frequent in tropical latitudes than in higher latitudes. (See Law 69.) On the other hand, droughts likewise are more fre-

198 Huntington, Earth and Sun, *loc. cit.*

199 Visher, S. S., Variation vs. Uniformity, *loc. cit.*, and Tropical Climates from an Ecological Viewpoint, *Ecology,* Vol. 4, pp. 1-10, Jan. 1923, and Vergleichung der Niederschlagsveränderlichkeit in niedrigen und mittleren Breiten, *Meteorolog. Zeitsch* Bund 41, Heft 2 Z. 46-49, 1924.

quent and protracted in tropical latitudes than in higher latitudes having similar average rainfalls. In parts of middle latitudes, where the normal rainfall is 40 inches (1000 mm.) or more, periods of a month without precipitation are very rare during the normal rainy season, while in the tropics even where the average rainfall is over 80 inches (2000 mm.) as in the Philippines, periods of several weeks with no rain are not very rare.[200]

The greater variation in annual rainfall in tropical latitudes than in higher latitudes appears to be related to annual contrasts in storminess. For example, some tropical localities are visited by several times as many hurricanes in one year as in another. In regions where hurricanes are almost lacking, as is the case of the equatorial stations mentioned above, there is nevertheless a sharp contrast in the annual number of disturbances produced by mild local storms or by distant hurricanes. In higher latitudes there is greater uniformity both in the number and in the severity of storms. This is partly because many of the tropical storms move poleward, where the meridians converge, and then move eastward, perhaps, nearly encircling the globe. Thus there are many more storms in high latitudes than in low. Storms are less severe in high latitudes than in low probably because they are accompanied by less condensation of water vapor. The energy liberated at condensation is the great source of the storm's energy. The cool temperatures characteristic of high latitudes permit a smaller moisture content than prevails in tropical latitudes. Hence cyclonic disturbances cause less condensation in high latitudes than in low, and therefore possess less energy.

200 Coronas, The Climate and Weather of the Philippines (Official), pp. 111-123, 1920.

CHAPTER V

MISCELLANEOUS LAWS OF CLIMATE

AIR PRESSURE

81. *Air pressure decreases with increased elevation* because the atmosphere envelops the rest of the earth. One half of the air is within 3½ miles (5.6 km.) of sea level and 3-4 within about 6.8 miles (10.9 km.). Near sea level, the decrease is about 4% per 1000 feet (304 m.), the barometer standing at about 29 inches (736 mm.) at 830 feet (253 m.) above sea level and at 28 inches (711 mm.) at 1800 feet (550 m.) instead of at 30 inches (760 mm.) as it does at sea level. The rate of decrease varies directly with altitude, however, being (at 45° F.) about 3% at one half mile and 2.7% at a mile. In other words, to have the pressure decrease 0.1 inch, the barometer must rise 92 feet at sea level (temp. 50° F.) 98 feet at an altitude of 1800 and 111 feet at a mile above sea level.[201]

Near sea level the air exerts a pressure of about 14.7 pounds per square inch, a ton to the square foot or 30 million tons per square mile. At a mile above sea level the pressure is about one sixth less and at two miles it is about 10 pounds per square inch.

Some effects of the decrease in air pressure upon insolation, radiation, wind velocity and evaporation have been given in previous laws (4, 37, 53). At 5000 feet, there are appreciable effects on some climatic elements, especially upon the rate of cooling in the shade, and some people are made nervous. At 10,000 feet the effects on man are more pronounced, and at 15,000 most men are made weak and often dizzy.

82. *There are seasonal and diurnal variations in air pressure* related to changes in temperature but with the opposite sign, falling as the temperature rises. In regions of radical seasonal temperature changes, the average pressures of July and January commonly differ by 0.4 inch, somewhat more than one per cent. (Over central Asia the range is 2.5%).

Large seasonal differences affect the average wind direction (Laws 28, 30, 33) and produce monsoons (Laws 28, 33). Diurnal differences of pressure are appreciable in all areas that possess a conspicuous diurnal range of temperature, the maximum coming about sunrise and the minimum in the late afternoon. Along sea coasts, pressure changes

[201] *Smithsonian Meteorological Tables,* loc. cit., Tables 51-64.

often lead to sea and land breezes, especially if the land experiences a sharp change of temperature and the water is cooler than normal (Law 46).

A minor type of variation in pressure is the semi-diurnal rhythm. The maxima occur about 10 A. M. and 10 P. M. and the minima about 4 A. M. and 4 P. M.. These are transposed upon the simple diurnal curves with the result that the daytime minimum are more pronounced than the nocturnal. The amplitude of the semi-diurnal fluctuations increase toward the equator and equinoxes and are greater on clear than on cloudy days and on land than on sea. Over the sea, in fact, the nocturnal amplitude is greater than the day-time. In the Pacific tropics, the day-time amplitude is 2 mm.[202]

83. *Barometric pressure varies from day to day* due to the influence of cyclonic storms (See Laws 84 and 85), and, in some places, with changes in the intensity and location of the semi-permanent areas of high and low pressure. In middle latitudes, interdiurnal changes of more than one per cent are common, 3 per cent. (one inch) frequent, and of 5 per cent. not very rare. In the tropics, a one per cent. fluctuation (⅓ of an inch) is fairly frequent and a 10 per cent range occasionally occurs in the paths of severe tropical cyclones. Tornadoes (See Law 86) occasionally cause yet greater changes of pressure, and thunderstorms smaller ones (Law 87). Interdiurnal changes of pressure associated with cyclonic storms are highly important both directly and as an indication of the coming change of weather. Changes associated with variations in the semi-permanent highs or lows often influence storm tracks and thus the weather.[203] On the borders of well-marked semi-permanent highs and lows such as the Aleutian and Icelandic lows and the North Pacific high, many of the strong winds result from a temporary steepening of the general barometric gradient.[204]

CYCLONIC STORMS.

84. *Tropical cyclones are whirling storms which occasionally powerfully affect wide areas especially along the margins of the tropics.* Most of the storms originate in latitudes 10°-15°; many of them travel westward hundreds of miles, and a large proportion enter middle latitudes. Some travel several thousands of miles before dissipating. A well-developed hurricane or typhoon is characterized by a steep baro-

---

202 Humphreys, Physics of the Air, p. 232, 1920.

203 Henry, A. J. and others, Weather Forecasting in the United States, 1916.

204 Hurd, W. E. and Tingley, F. G., Monthly reports on the Weather of the North Pacific, *Mo. Weather Rev.*, 1918-1923. See also Daingerfield, L. H., the Kona Winds of Hawaii, *Mo. Weather Rev.*, Vol. 49, pp. 327-329, 1921.

metric gradient towards a central calm, where the pressure may be below 28 inches (711 mm.); they have winds of hurricane or gale force over a belt 300 miles across on the average in the tropics, and yield heavy precipitation. Usually they travel about 300 miles a day in the tropics, but more rapidly in higher latitudes where they also commonly increase in size but diminish in severity. Tropical cyclones differ greatly, however, in size, intensity, speed and in other respects. Upwards of 35 hurricane-producing storms occur each average year and more than twice as many gale-producing storms. Still less intense cyclonic disturbances are more numerous and are likewise very important yielders of rainfall especially on the leeward slopes in the trade-wind belt. Tropical cyclones are important in many respects, discussed elsewhere.[205]

85. *Cyclonic storms, "Lows", are numerous in mid-latitudes and dominate the weather there,* producing frequent striking changes in wind direction and velocity, in temperature, humidity, cloudiness and precipitation. They are great whirls averaging nearly a thousand miles across which move eastward (east, northeast or southeast) at an average rate of about 400 miles per 24 hours, in summer and 800 miles in winter. Many of them travel several thousand miles. They cause precipitation in wide areas which would be dry if only the westerlies or monsoons prevailed, as for example between the Rockies and Appalachians in North America, in southeastern Europe, southern Australia and in southeastern South America.

Lows are sometimes accompanied by destructive winds and torrential rains, or by "hot waves," and in winter, by heavy snowfall or sleet.[206]

Thunderstorms and tornadoes also are associated with lows (See Laws 86, 87). In mid-latitudes, scientific weather predictions are largely based upon a study of the special characteristics of approaching cyclonic disturbances.[207]

The frequent change of weather produced by the passage of lows and highs puts a premium on alertness and forethought and apparently stimulates both intellectual and physical activity.[208]

---

[205] Visher, S. S., Tropical Cyclones of the Pacific and their Effects, Monograph of the Bishop Museum, Honolulu, 1924. Newnham, E. V., Hurricanes and Tropical Revolving Storms, *Geophysical Memoirs,* No. 19, British Meteorological Office, 1923.

[206] Ward, R. DeC., Hot Waves and Cold Waves in the United States, *Scientific Monthly,* Vol. XVI, pp. 449-470, 1923 and Vol. XVII, pp. 146-167, 1923.

[207] Henry, A. J. and others, Weather Forecasting in the United States, 1916, Shaw, N., Weather Forecasting, 1919.

[208] Huntington, E., Civilization and Climate, 1915, World Power and Evolution,

Variations in the courses followed by the disturbances and in their intensity, speed, and frequency cause most of the variations from year to year in temperature, winds and precipitation (Laws 21, 26, 44, 79, 80). Long continued changes in storm paths and intensity may have been important causes of changes of climate including the glacial periods.[209]

Many of the lows present in mid-latitudes originated as tropical cyclones. Others "bud off" from the semi-permanent lows such as "the Aleutian Low," and yet others originate on land. Cyclonic storms obtain their energy from three great sources, (1) the latent heat of condensation, (2) the direct absorption of solar energy by the atmospheric moisture of the lows; (3) the under-running of the warm winds from lower latitudes by the colder winds from higher latitudes. After a large mass of air is set rotating, its inertia and gyroscopic momentum and small friction often permit it to travel far without receiving much additional energy from condensation. But cyclones usually intensify in winter when approaching open bodies of water such as The Great Lakes or the sea, both because of increased condensation and because of sharper local temperature contracts. Conversely, they weaken when crossing a cold region like northern Asia in winter.[210]

86. *Tornadoes occasionally cause local destruction in most warm plains.* They are tiny cyclones characterized by very low pressures at their center and winds of destructive violence over a belt a quarter of a mile (½ km.) wide on the average, and 20 miles (32 km.) long. They usually develop along the windshift line of lows, and in the clouds, later extending downwards to the earth. A hundred or so occur annually in the United States, the center of abundance being in Missouri, and the month of greatest frequency being June. All states east of the Rockies have been visited, however, and likewise southern Canada, and tornadoes have been recorded in all months somewhere in this area.[211]

Tornadoes are probably as frequent and widespread in Australia

1919. Visher, S. S., Economic Geography of Indiana, pp. 73-88, 110-112, 167, 213-218, 1923.

209 Huntington and Visher, Climatic Changes, their nature and causes, 1922, and Huntington, Earth and Sun, 1923.

210 Shaw, Jefferies, and others, The Energy of Cyclones, a symposium, *Mo. Weather Rev.*, Vol. 49, pp. 3-5, 1921. Summed up and extended in Visher, Tropical Cyclones, loc. cit.

211 Ward, R. DeC., Tornadoes in the United States, *Quart. Jour. Royal Meteorol. Soc.*, Vol. 43, July, 1917. Abridged in Nature (London), Vol. 101, pp. 395-399, reprinted in Smithsonian Annual Report 1918, pp. 139-145, 1920.

as in the United States[212] and are rather common in western Africa.[213] Typical tornadoes occur occasionally in Europe,[214] in Fiji[215] and in the Dutch East Indies,[216] India, China and Japan, and similar storms in South America. Water spouts are tornadoes at sea.

THUNDERSTORMS.

87. *Thunderstorms yield most of the rainfall of warm regions and cause sharp temporary changes of wind and temperature.* The associated squalls, lightning and hail occasionally are locally destructive. Thunderstorms are caused by the sudden rise of a large mass of relatively warm moist air, and hence are most frequent when convectional overturning is greatest, which is during the summer, (except on the sea in high latitudes, where they are most frequent in winter, (See Law 40 for reasons). Diurnally, thunderstorms are most frequent in the late afternoon or early morning (See Law 76.) Regionally, they are most numerous in the humid parts of the tropics where several occur each week during the rainy season. They are rare, but not unknown, in polar regions and rare in the deserts and hence in the tradewind belt on the ocean. In the United States they are most frequent in the humid southeast and least frequent along the Pacific coast, where, because of unfavorable temperature conditions, little of the rainfall occurs in summer, the season of strong vertical convection. (See Law 73).[217]

In middle latitudes, most thunderstorms are associated with lows and in the tropics many of them with weak cyclonic depressions. Most well-developed tropical cyclones are accompanied by severe thunderstorms.

LIGHT.

88. *The quality and intensity of sunlight varies from place to place and from time to time.* The light is most intense where it passes through least atmosphere, where there are fewest atmospheric particles to reflect or absorb it, and where the earth's surface is a good reflector. Hence it is most intense on the snow fields on tropical mountains, above

---

212 Hunt, H. A., Director of Commonwealth Bureau of Meteorology, oral communication. See also Visher, S. S., Australian Hurricanes and Related Storms, Official Yearbook of Australia, No. 17, pp. 80-84, 1923.

213 Newnham, E. V., Storm Squalls and Tornadoes of West Africa, pp. 257-268 *Geophysical memoir* No. 19, 1922.

214 Espy, J. P., Philosophy of Storms, 1841, Lempfert, R. G. K. Meteorology, pp. 174-176, 1920.

215 Personal experience.

216 Braak, C., The Climate of the Netherlands Indies, Vol. 1, pt. 2, pp. 44-45, 1922.

217 Humphreys, W. J., Physics of the Air, 324-331, 1920.

the clouds, when the sun is overhead, and least intense in high latitudes in winter where the atmosphere is filled with haze and when there is no snow. Because atmospheric moisture is an excellent absorber of radiant energy, the sunlight is relatively intense in arid regions, and more intense than normal whenever anticyclones bring dry air to normally humid regions. Accompanying the variations in intensity are variations in the proportion of ultra-violet rays, which are much more abundant in tropical regions than in high latitudes. This fact may interfere with "the conquest of the tropics by white man."[218]

Sensible Temperature

89. *The temperature often feels warmer or colder than the thermometer indicates.* Sunshine and calm feel notably warmer than shade and wind, and dry air feels warmer than moist air below about 50° F., (10° C.) but above about 55° F. moist air feels the warmer. When warm, dry air feels cooler than moist air because it induces more evaporation from the skin, and evaporation is a cooling process. The wind is important in increasing evaporation but especially in replacing the warm air in contact with the skin with cooler air. At low temperatures, moist air feels cooler than dry air, partly because it is a better conductor of heat, but chiefly because of the evaporation on the skin of the tiny droplets of moisture or spicules of ice suspended in moist air when cold.

Foehns.

90. *Many mountain valleys and leeward slopes have a peculiar climate because of local hot winds,* "foehns" or "chinooks." Temperatures and sunshine average abnormally high in such areas and humidity and precipitation exceptionally low. Foehns occur in nearly all mountainous regions but especially where and when large quantities of moisture have been precipitated on the windward slopes by strong winds. Condensation raises the temperature of the air, and if the wind velocity is strong, the excess heat is not all lost by radiation in crossing the mountains; while descending, compression increases the temperature still further, often resulting in a very dry wind. Foehns, called chinooks, are often prominent in the Western United States, raising the temperature several degrees in a few minutes and evaporating a foot or more of snow in a few hours.[219]

---

[218] Woodruff, Maj. C. E., The Effect of Tropical Light on White Men.

[219] Ward, R. DeC., Hot Waves and Chinooks in the United States, *Scientific Monthly*, Vol. XVII, pp. 160-167, 1923, and Burrows, A. T., The Chinook Winds, *Jour. of Geog.*, Vol. 2, pp. 124-136, 1903.

In Switzerland, where the name "foehn" was first used, they are often so dry, strong, and hot that the danger of conflagrations are greatly increased, and special precautions are taken.[220]

Foehns occasionally occur far from mountains and produce great temporary aridity.[221]

---

220 Salisbury, Barrows and Tower, Elements of Geography, p. 138, 1912.

221 Brooks, C. F., A hill-top foehn, *Mo. Weather Rev.*, Vol. 47, p. 567, 1919. McAdie, A. (A Cloud Atlas, p. 52, 1923), reports that the relative humidity on Blue Hill, Mass., was only 1.4% on April 8, 1917.

INDEX